A STUDY TO ASSESS THE EFFECTS OF DIESEL EMISSIONS ON AIR QUALITY IN THE PCS MINING LANIGAN DIVISION UNDERGROUND POTASH MINE

Final Report

by

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Work on the project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy Mines and Resources, Canada

DSS FILE NUMBER: 26SQ.23440-4-9128
DSS CONTRACT SERIAL NUMBER: OSQ84-00228
CANMET PROJECT NUMBER: 320105
CANMET SCIENTIFIC AUTHORITY: Dr. M. Gangal

Date: February 15, 1985

OCT 3 8 1985
MICROMEDIA

81 pp.

This report should be cited as Contract Report No. OSQ84-00228

TABLE OF CONTENTS

	Page
FOREWORD	1
EXECUTIVE SUMMARY	2
EXECUTIVE SUMMARY (FRENCH LANGUAGE)	4
INTRODUCTION	6
Objective	10
Scope	10
DESCRIPTION OF MINE AND MEASUREMENT METHODOLOGY	11
Description of Mine	11
Mining Operation Studied	12
Measurement Methodology	15
Measurements Included in Study	23
RESULTS	31
Mining Conditions for the Study	31
Data Analysis	42
CONCLUSIONS AND RECOMMENDATIONS	65
REFERENCES	70
APPENDIX I	71
APPENDIX II	74

LIST OF FIGURES

Figure		Page
1	Map covering portion of mine studied.	13
2	Sketch illustrating drive location development operation studied.	16
3	Typical pollutant characteristic curve.	18
4	Relationship between ratio of air flow rate to produced BHP and mine air CO_2 concentration.	22
5	Conditions on 11/26/84.	35
6	Conditions on 11/27/84.	37
7	Conditions on 11/28/84.	38
8	Conditions on 11/29/84.	39
9	Conditions on 11/30/84.	40
10	CO characteristic curve for truck, November 26-30, 1984.	47
11	NO characteristic curve for truck, November 26-30, 1984.	48
12	NO_2 characteristic curve for truck, November 26-30, 1984.	49
13	SO_2 characteristic curve for truck, November 26-30, 1984.	50
14	Particulate matter characteristic curve for truck, November 26-30, 1984.	51
15	CO characteristic curve for wall, November 26-30, 1984.	52
16	NO characteristic curve for wall, November 26-30, 1984.	53
17	NO_2 characteristic curve for wall, November 26-30, 1984.	54
18	SO_2 characteristic curve for wall, November 26-30, 1984.	55
19	Particulate matter characteristic curve for wall, November 26-30, 1984.	56
I-1	Illustration of procedure used to develop the characteristic curves presented in this report.	72
II-1	Calculation procedure for NO and NO_2 by Palmes samplers.	77

LIST OF TABLES

Table		Page
1	Applicable Standards and Other Pertinent Limits	9
2	Description of Measurements	24
3	Daily Record of Measurements	25
4	Sampling Conditions	33
5	Average Daily Concentration - Truck, Drift Wall, Upstream, and Mine Intake	43
6	Absolute Concentration Differences; Truck & Drift Wall	57
7	Slopes of pollutant characteristic curves	58
8	Operating Concentration as % of Assumed Limit	60
9	Various Calculated Parameters	63
II-1	Daily drift NO and NO_2 concentrations by the Ecolyzer 7230 and Palmes samplers and ratios as measured	75
II-2	Daily drift NO and NO_2 concentrations by the Ecolyzer 7230 and Palmes samplers and ratios as used	76

FOREWORD

The study reported here was a cooperative effort which included the authors, PCS Mining, Saskatoon, PCS Mining, Lanigan Division and CANMET.

The authors want to express sincere thanks to Gopal Kunchur of PCS Mining, Saskatoon whose interest and initial contacts provided the spark which ultimately resulted in this fairly extensive successful project. We also thank Mr. Kunchur for his hands-on participation in all phases of the planning and field work including the actual sampling of the mine air itself.

We also wish to thank Dave Greenberg of the PCS Mining, Lanigan Division who received, stored and returned the instruments loaned by CANMET, scheduled the mining activities to coincide with the study dates and supplied the necessary help to do the field work. We realize these services were the result of considerable effort.

The daily assistance by Bert Roberts who at the request of Dave Greenburg provided transportation, measured air flows and willingly assisted us in all phases of the field work is greatly appreciated. We also thank Bert for his efforts subsequent to the field work in gathering information needed to make this report more complete.

Finally we are especially grateful to Dr. Mahe Gangal, the Scientific Authority for CANMET, the sponsor for this study. We appreciate the effort put forth by Dr. Gangal in planning the work, supplying the instruments and providing helpful advice during all phases of the study. We also acknowledge the participation of Don Dainty of CANMET in planning this effort. We fully realize that Don's continued interest and enthusiasm has had much to do with making the CANMET underground diesel emissions program so successful.

EXECUTIVE SUMMARY

A study was conducted during November 1984 of the air quality in a diesel truck haulage operation in the PCS Mining Lanigan Division located near Lanigan, Saskatchewan. The objective was to develop baseline diesel pollutant measurement data for the 'drive location development' operation considered to be the worst case diesel situation in the mine.

CO, NO, NO_2 and particulate matter data were measured over a 5-day period along with CO_2 at 4 locations. Data were analyzed to determine how the above pollutants, as well as SO_2 and SO_4 compare to the applicable standards and the air quality index. The study was conducted to reveal the order of pollutants from most to least critical, to evaluate the need for controls and to provide a basis for sound engineering judgements about the types of controls and which controls would be most effective.

The results are presented as pollutant characteristic curves. In general diesel pollutant concentrations in the dead end drifts produced by the operation studied were found to be lower relative to the standards than salt dust. Special treatment of the data was required because of significant concentrations of the pollutants and CO_2 due to direct-firing of natural gas to warm the air taken into the mine.

NO, SO_4, and SO_2 were in general below typical levels found in previous studies, but particulate concentrations in the drift exceeded levels measured earlier. NO_2 was considered to be the diesel pollutant of major concern and the one that needs to be controlled by avoiding recirculation or long residence time in the mine ventilation system which allows NO to react with oxygen in the air to produce NO_2.

A maximum CO_2 control level of 0.18% is recommended for the conditions studied to hold the various pollutants below their assumed limits. This CO_2 control level will need to be adjusted by the procedures presented if the background pollutant and CO_2 concentrations change significantly. Significant changes in background concentrations will occur if the direct-firing of natural gas in the mine intake air is changed or eliminated as anticipated for the warm season. The need for specific air quality measurements and monitoring of fuel sulfur levels is also discussed.

RESUMÉ

En Novembre 1984, une étude a été menée sur la qualité de l'air dans une mine pendant une opértion de remorquage par camion Diesel. Les mesures ont eu lieu dans la mine PCS Mining Lanigan Division près de Lanigan, Saskatchewan. L'objectif était de développer une base de données de réference a propos de la pollution par un diésel. Cette étude sert dans le cas de developpement de nouveaux tunnels, operation considérée comme étant la situation de pollution la plus mauvaise dans la mine.

Les taux de CO_2, CO, NO, NO_2 et de particules ont éte mesurés pendant cinq jours en quatre endroits différents. Pour les polluants ci-dessus, ainsi que pour SO_2 et SO_4, les résultats ont été comparés aux normes en vigueur et à l'indice de qualité de l'air. L'étude a permis de déterminer pour chaque polluant le niveau critique, d'évaluer le besoin de contrôle et de fournir des données pour une décision bien fondée concernant les types de contrôles nécessaires.

Les résultats sont présentés sous forme d'abaques de caractéristiques des polluants. En général, pour l'opération étudiée, les concentrations des gas d'échappement de diésel dans les bouts de tunnels sont moins élevées par rapport aux standards que celle de la poussière de sel. Un traitement spécial des mesures était nécessaire à cause des polluants et du CO_2 produits également pendant le chauffage de l'air pour la mine par combustion libre de propane.

Les Taux de NO, SO_4, et SO_2 sont inférieurs aux taux trouvés dans de précédentes études, mais la concentration de particules dans le tunnel excède les niveaux trouvés précédement. NO_2 est le facteur le plus inquiétant. Afin de contrôler la quantité de NO_2, il est nécessaire

d'éviter la réaction de NO avec l'oxygène de l'air en empêchant une re-circulation et une longue station de ces gaz dans le systeme d' aeration de la mine.

Une concentration maximale de CO_2 de 0.18% est recommendée dans les conditions étudiées afin de maintenir les différents polluants en dessous des normes considérées. Cette limite de CO_2 devra être modifiée suivant les procédures présentées, si les conditions de pollution et de concentrations de CO_2 changent de façon conséquente. Ces changements dans l'environnement peuvent être par exemple dus à l'interruption ou à la modification du système de chauffage de l'air par combustion de propane. Les besoins pour des mesures de qualité de l'air et des contrôles de niveau de sulfures sont aussi abordés.

INTRODUCTION

Air quality monitoring in an underground mine poses numerous special requirements for the techniques used due to the peculiar characteristics of this environment. The use of mobile diesel vehicles underground results in an even more unique monitoring situation with the need for additional special considerations. Underground air quality measurements have, nonetheless, been made over the years, with many such measurements reported in the published literature. However, due to the difficulty in interpreting such data the results have, for the most part, not been used other than as a means of determining whether or not a particular pollutant exceeded the standard when measured.

Until recently it has been the opinion of many that little in the way of useful information for making engineering judgements could be derived from such measurements. However, recent research sponsored in part by CANMET and in part by the U.S. Bureau of Mines has resulted in a systematic coordinated approach to the measurements, data analysis, and interpretation, and it has become evident that much useful information can be developed by monitoring and that sound engineering judgements can be made, based on the findings.

In the past, measurements on and around mobile diesel equipment have usually consisted of one or two short term detector tube grab sample readings to determine the concentration of a single pollutant. If at the moment measured, the concentration was in compliance with the applicable standard, nothing more was done with the data. However, the recently-developed approach (1) has made it possible to determine from the data the effects of various mine air quality control techniques and to recommend

specific changes which will improve air quality and(or) reduce costs. This is not to insinuate that all the measurement problems are now solved. Rather the newly-developed approach has shown more clearly what instrumentation and technology advances are needed to arrive at a satisfactory overall solution.

The application of these new developments in the PCS Mining Lanigan Division is based on concerns by the PCS Mining Management about the effect of diesel emissions on the mine air quality. Monitoring to date in the Lanigan mine has been carried out by daily detector tube spot checks of the concentrations of the various gases of concern. As this report will demonstrate, proper measurements at no greater frequency than the past spot checks can provide a great deal of useful information about mine air diesel pollutant concentrations when used in conjunction with the findings reported herein. Total particulate matter has also been spot checked in the past, but no effort to date has been made to distinguish between diesel particulate and ore dust.

The present study involved making measurements on and near a diesel truck which was used to haul the ore from the continuous miner to the conveyor during the development of new drifts and(or) crosscuts. This development operation can result in dead end drifts 200 ft or more in length such as the one monitored in the present study. Discussions with mine personnel have indicated that the operation monitored by us typically results in the highest levels of diesel pollutants to be found in the mine (worst case).

The data are analyzed in this report to establish CO_2 concentration limits below which air quality will be satisfactory (in regard to the diesel

pollutants measured) and to provide sound recommendations about how to control mine air diesel pollutant concentrations most effectively when necessary.

Concentration limits for the diesel air pollutants of most concern differ somewhat from one mine to another based on local regulations. The objective of engineering controls is to assure that all the applicable limits are complied with. To date, the air quality control technique most used underground has been to regulate the volume of dilution air (ventilation). The amount of ventilation is usually set to maintain the critical pollutant (the one that requires the most dilution to remain below the specified limit) below its specified limit. In general, air quality standards (assumed limits) determine the amount of control that is needed. Thus, changes in the standards may require reinterpretation of the results of an air quality study.

Table 1 lists various applicable standards along with limits recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). Most air quality standards in the U.S. and Canada are based to at least some extent on the ACGIH recommended limits.(2)

Saskatchewan has lower limits for miner exposure to CO (25ppm) and NO_2 (2 ppm).

Compliance monitoring in the PCS Mining Lanigan Division has in the past consisted primarily of making occasional NO_2 and CO detector tube readings to assure that the concentrations are always below these standards.

Table 1. Applicable Standards and Other Pertinent Limits

Substance	Saskatchewan limit	1984 ACGIH Recommendation TLV**	STEL***
CO	25 ppm*	50 ppm	400 ppm
CO_2	0.5%	0.5%	
NO		25 ppm	35 ppm
NO_2	2 ppm*	3 ppm	5 ppm
SO_2		2 ppm	5 ppm
H_2SO_4		1 mg/m^3	3 mg/m^3
Dust (total = TPM)	10 mg/m^3**** (total nuisance dust)	10 mg/m^3	
Dust (respirable = TRPM)		5 mg/m^3	
RCD		*****	

Other limits assumed in this report

Respirable combustible dust (diesel particulate) - 2 mg/m^3

Air quality index (AQI) - 4 (3 is recommended action level)

* Mine regulations, 1978, Prov. of Sask. part XXII, Section 444.04 (B) (1) (2) (3)

** Time weighted average for work shift

*** Short term exposure limit

**** Proposed limit for total dust

***** We use the 2.0 mg/m^3 for coal due to the similarity between the two particulate types.

Objective

The objective of the present study was to develop baseline diesel pollutant measurement data for the operation which represented the worst case of miner exposure to diesel emissions in the PCS Mining Lanigan Division. The purpose of the data is to determine how various pollutant concentrations compare to the applicable standards, and explain why the measured concentrations occur, to reveal the order of diesel pollutants from least to most critical, to aid in the evaluation of the need for controls, and to provide a basis for sound engineering judgements about the types of control which would be the most effective in either reducing costs or improving air quality with regard to specific pollutants and(or) standards.

Scope

The study involved simultaneous time-weighted-average concentration measurements of CO, CO_2, NO, NO_2, and respirable or total particulate matter at 4 locations which would best characterize the air quality and the effects of controls for the operation selected. This included the collection of a fuel sample, the analysis of which allowed us to calculate the concentrations of SO_2 and SO_4 at each location. The particulate matter samples were analyzed for their carbon and hydrogen contents which allowed us to calculate the concentrations of both the diesel and nondiesel fractions.

The study involved five days of sampling the underground diesel operation selected. The data were analyzed using a recently-developed computer program that makes use of this coordinated approach to monitoring to produce results which satisfy the objectives.

DESCRIPTION OF MINE AND MEASUREMENT METHODOLOGY

Description of Mine

The PCS Mining Lanigan Division is located just west of Lanigan, Saskatchewan. The potash ore body is 3250 ft below the surface (1650 ft below sea level). The valuable mineral, sylvite (potassium chloride), makes up about 40% of the ore matrix. The remainder is largely halite (sodium chloride) which is of no value due to iron staining in the grains, and this fraction is rejected in subsequent flotation processing of the ore. The ore contains no appreciable silica, the substance which in many mines has the greatest effect on airborne dust standards.

The overall underground occurrence of potash is mammoth, underlying much of the Saskatchewan Province. The PCS Mining Lanigan Division itself has tunnels running throughout this underground salt layer that underlie an area on the surface which is about 3 1/2-miles long by 2 1/2-miles wide.

About 170,000 CFM of fresh air enters the mine through the ore shaft and exhaust air leaves the mine through the man and materials shaft. These two shafts are connected by less than 1000 ft of underground tunnels. Air doors and air bulkheads of various types block the various tunnels connecting the fresh and exhaust air routes and thereby direct the fresh air from the ore shaft to the distant extremities of the mine before it is exhausted through the man and materials shaft. Close proximity of intake and exhaust air shafts results in the potential for an air door to be left open for a period of time allowing the fresh air to short circuit the mine extremities and pass directly to the mine exhaust air shaft. Such a situation, which was observed once during the present study, could result in a significant build up of airborne gaseous pollutants, although the PCS

Mining Lanigan Division tunnels are large and numerous and tend to significantly increase the time required for such concentration build-ups to occur. The possible build-up of diesel pollutants is, of course, a major concern to mine personnel responsible for air quality control. Because the PCS Mining Lanigan Division employs diesel equipment to only a very limited extent for development-type mining only, the possibility of a serious problem occurring would seem to be remote.

Intake air to the Lanigan Mine as mentioned above, passes down the ore shaft which is surrounded by wet ground. The mine air is heated to prevent expansion and contraction of the steel lining. The fresh air temperature is, therefore, controlled by direct firing of natural gas in the fresh air before it passes down the shaft. However, the combustion of natural gas results in exhaust emissions which contain many of the diesel pollutants of concern (though normally in lower concentrations) and this made it necessary for us to sample in such a way that the two emissions sources could be distinguished from one another.

Mining Operation Studied

Figure 1 is a map covering the portion of the mine with which our study was concerned. The horizontal straight line distance from the intake air shaft (not shown in Figure 1) to the development heading we monitored (BO489) was at least 3 1/2 miles. Thus the 'fresh' air to this mine area had to travel a much greater distance since it is directed by air controls to the various parts of the mine in series. A limited amount of diesel activity upstream in other parts of the mine, no doubt, affected our readings to a limited degree. Figure 1 shows more than a mile of each of the two parallel drifts P.E.5 and BO4. The Figure shows how these drifts were connected on the far end upstream of our study drift (BO489) by #7

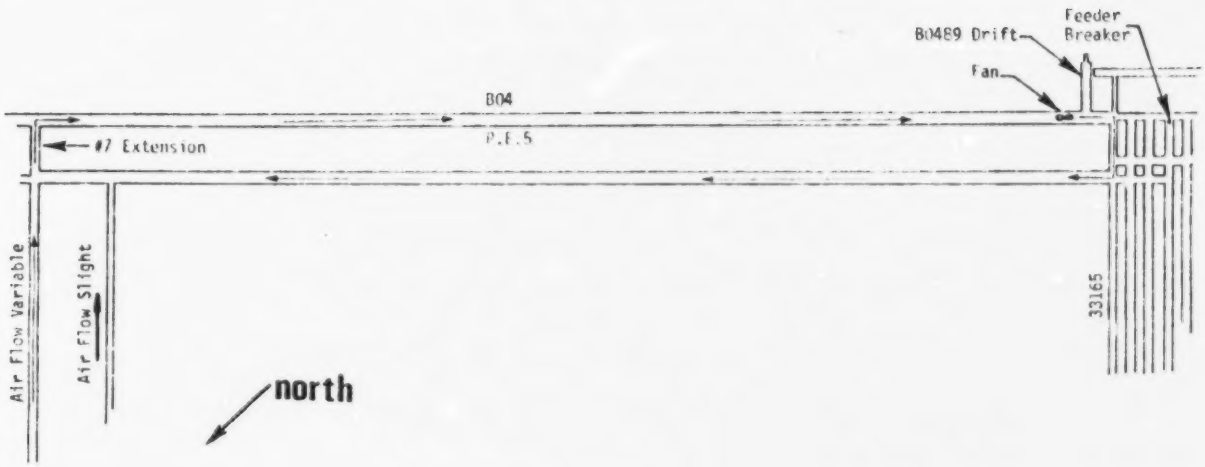

Figure 1. Map covering portion of mine studied.

extension and on the near downstream side of BO489 by 33165. The intersection between BO4 and BO489 was in effect, the first crosscut where most of our observations were made.

The Joy 30-in x 30-HP axial fan located about 200 ft upstream from BO489 was normally 'on' during the study drawing in upstream air and blowing it through this BO4/BO489 crosscut. We observed the tendency for some of the air from this crosscut to recirculate directly back to the free-standing fan. Another observation was the tendency for the fan to cause recirculation around the entire loop consisting of BO4 - 33165 - P.E.5 - #7 extension.

The mine operates around the clock every day except Wednesday on the day shift when maintenance activities are scheduled. The bulk of mining activity (95+%) is performed by the 'electrically powered continuous miner cutting and conveyor haulage combination' where the continuous miner automatically places the ore on extensible trailing conveyors. Thus no diesel haulage vehicles are ordinarily needed. Diesel truck haulage such as we studied is used only for the operation referred to as 'drive location development' or for the operation referred to as 'pure development' of cross rooms. 'Drive location development' is used to start the first 200 ft or so of the 4000 ft long drifts (rooms) mined by the 'continuous miner - extensible conveyor' combination. 'Pure development' of cross rooms involves mining occasional drifts which connect the parallel 4000 ft long main drifts. The usual drift is 50 ft wide and about 9 ft high. The usual pillar is 75 ft thick and over 1000 ft long between the cross rooms.

There is no drilling in the Lanigan Mine and roof bolting is limited to those locations where the roof is uneven such as at the start of a new drift. This bolting operation is carried out by a John Deere model JD4219DT bolter powered by a diesel engine rated at 62 HP at 2500 RPM.

Figure 2 is a sketch illustrating the drive location development operation studied. A 240 ft long drift was cut and most of the cutting took place during the 5 day shifts while we were there making measurements. The first 200 ft was mined in two 26-ft-wide passes of the continuous miner. The overall width was actually about 47 ft due to overlap on the second pass. The last 40 ft of length was mined by a single pass originating in the center of the end of the first 200 ft.

Details of the operation studied (Figure 2) were as follows. The 37-ft-long by 26-ft-wide by 9-ft high 4-rotor Marietta Miner (Model #890 AW4) cut the ore and dropped it onto the floor immediately behind the miner. This ore was picked up by a 26-ft-long by 9-ft-wide by 3-ft-high model 968 electrically-powered Goodman loader which conveyed it into the telescoping box of a 20-ton Wagner truck that was backed up to the loader. The Wagner truck was powered by a Deutz F8L-714 diesel engine rated at 195 HP at 2300 RPM. This engine idled during the loading operation except while the truck moved to reposition itself with respect to the loader. These trucks use PTX catalytic converters to control carbon monoxide emissions.

When the truck was filled, the ore was hauled about 300 ft downstream in B04 past 33165 to a feeder-breaker which broke it up into smaller chunks and fed it onto a conveyor.

Measurement Methodology

The general approach to measurements is outlined in Reference 1. The theoretical basis of the newly developed methodology which is discussed in detail in References 1, 3 and 4 includes the following approach to the measurements:

1. Diesel exhaust pollutant concentrations are measured primarily as time-weighted-averages simultaneously with the diesel-produced CO_2

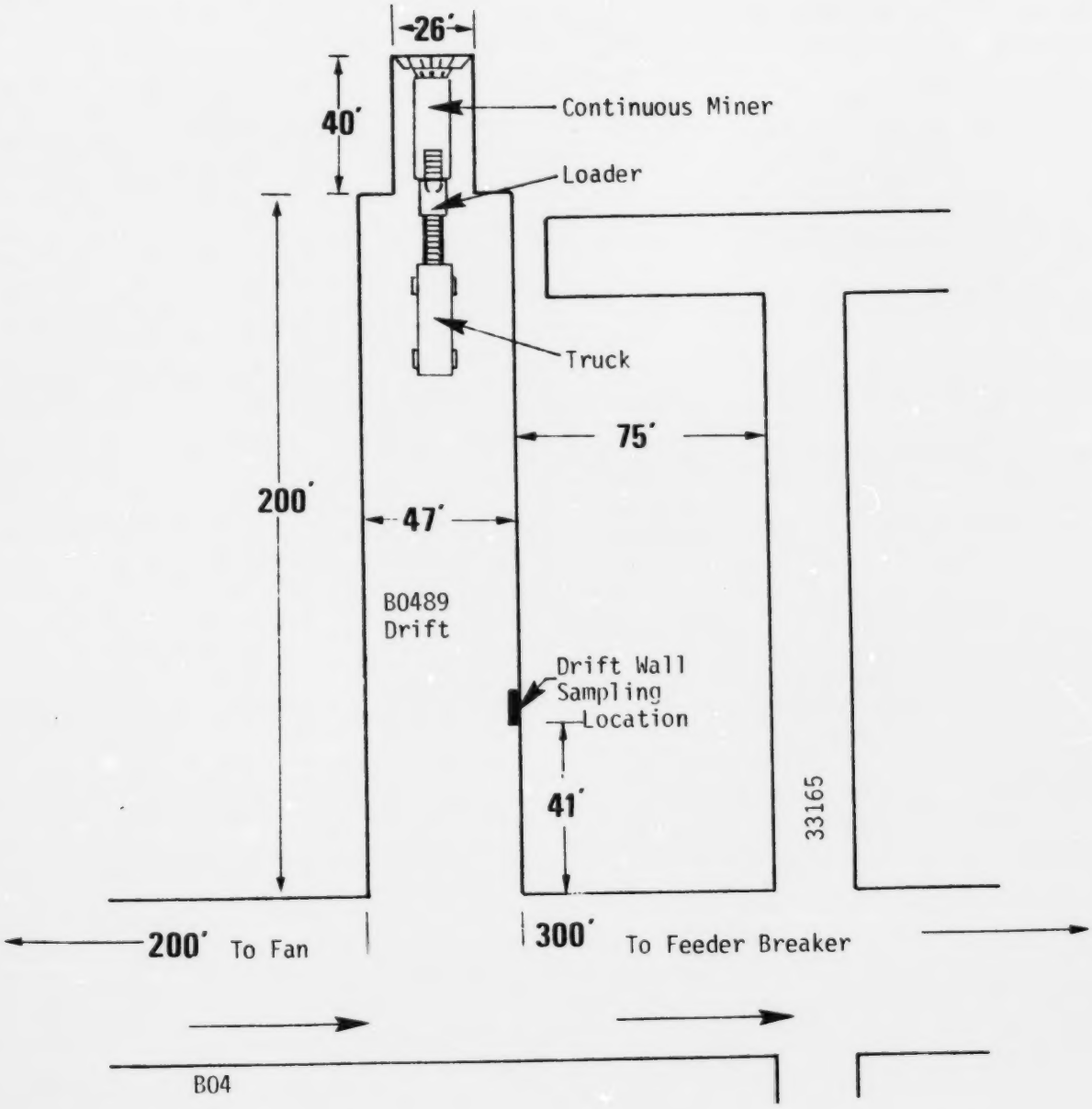

Figure 2. Sketch illustrating drive location development operation studied.

concentration on-board the diesel-powered vehicle near the operator position or at a fixed-point location nearby where concentrations are affected by the diesel-vehicle of concern, and at a fixed point station (background) upstream from the mining operation to obtain the pollutant concentrations of the incoming air.

2. Data are analyzed by a computer program which normalizes each diesel pollutant concentration relative to the CO_2 concentration measured simultaneously at the same location, and calculates a number of parameters that are useful for interpreting the data. The effects of background concentrations are separated from those due to the diesel engine of concern in the analysis.

Using this coordinated approach to sampling and data analysis makes it possible to express diesel pollutant concentrations found in the mine air in terms of the concentrations which would occur at any given volume dilution ratio -- (volume of fresh air + exhaust)/ (volume of exhaust). An important task performed by the data analysis computer program is to plot each diesel pollutant concentration against the simultaneously-measured CO_2 concentration. We refer to such a plot as a "pollutant characteristic curve". Figure 3 is an illustration of a pollutant characteristic curve (zero background pollutant concentration with CO_2 assumed to be the .035% found in outside air) which points out various important features.

The time-weighted-average pollutant concentrations measured on the truck and on the drift wall are plotted as characteristic curves for each pollutant species. If the diesel engines of the trucks emit the various pollutants and CO_2 in roughly the same relative proportions from day to day, the plots will produce fairly straight lines. In the present study, we gathered data for five days of the mining operation. The lines were

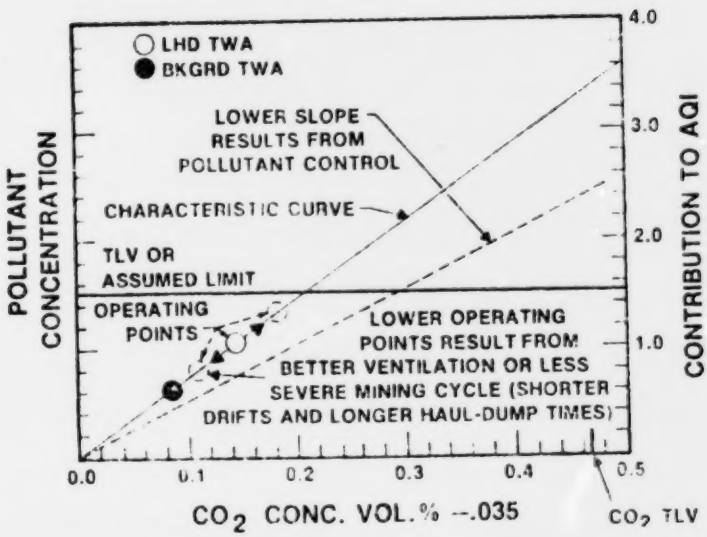

Figure 3. Typical pollutant characteristic curve.

constructed and the slopes determined by a weighted least squares curve fit; the procedure for preparing these curves is discussed in Appendix I. Each data point on the line is called an "operating point" since the position of a point along the line depends upon the amount of dilution per unit of exhaust produced. The amount of exhaust produced depends on the mining cycle and number of vehicles and the amount of dilution is determined by the ventilation conditions for that day. The magnitude of the slope of such a characteristic curve is a measure of the quantity of the pollutant generated by the diesel engine per unit of CO_2 generated (CO_2 is generated in direct proportion to the quantity of fuel consumed or of brake horsepower output). The slope can be decreased by improving the control of the particular pollutant with aftertreatment devices or by changing the design of the engine. Poor maintenance or engine mechanical problems can also affect the slope. Maintenance effects can cause either increases or decreases in the slopes with many maintenance problems resulting in particulate increases and NO or NO_2 decreases, both of which result from reduced combustion temperatures. The slope of a pollutant characteristic curve is very useful because it expresses the pollutant concentration in a manner which is independent of the amount of dilution which has taken place subsequent to leaving the tailpipe. Furthermore, this slope is directly related to the quantity of the pollutant emitted per unit of fuel consumed or per unit of brake horsepower output. These factors make it possible to analyze and interpret air quality measurement data taken in mine production operations over several days where the ventilation and the mining cycle change from day to day.

The important concept to understand is that the slope of the characteristic curve is an expression of the pollutant concentration that is

characteristic of the particular vehicle under the mining load cycle conditions tested and is independent of the amount of ventilation used. Thus, if the slope doubles, it means the particular vehicle is emitting twice as much of the particular pollutant per unit of CO_2 produced (or of fuel consumed or of output horsepower). The TLV or the assumed ambient limits are imposed on the plots so as to graphically display the CO_2 concentration at which the limits will be exceeded and the relative position of each days 'operating points' in relation to the limits. This allows us to monitor for CO_2 only, once the characteristic curves are developed, but occasional simultaneous checks of a particular pollutant and CO_2 can be extremely valuable in verifying that the characteristic curve still represents the conditions. A characteristic curve is constructed and analyzed for each pollutant or calculated index.

When background concentrations are significant and variable as in the Lanigan Mine, these must be checked also and treated in the manner described in Appendix I.

It is important for understanding the characteristic curves to know that the background concentration affects the position of the characteristic curve, but not the slope. As mentioned earlier, natural gas is burned in the PCS Mining Lanigan Division intake air during the winter and this natural gas produces measureable concentrations of the diesel pollutants of concern along with high CO_2 concentrations. Because of these natural gas emissions, the characteristic curve, which for zero backround would intersect the horizontal axis (abscissa) at about .035% CO_2 (or at zero if CO_2, %-.035 is plotted on the abscissa), intersects the abscissa at much higher CO_2 percentages. Thus the curves developed in this study where natural gas was burned would not hold for the warm conditions where no

natural gas would be burned. To use these curves in the summer it will be necessary to construct a characteristic curve parallel to the present one (same slope), that passes through the background pollutant and CO_2 readings for that time period as explained in Appendix I. In the summer we would expect the background CO_2 reading to be near the .035% for outside air and the other pollutant background readings to be near zero. Thus the curve would probably intersect the abscissa at .035% CO_2.

Another concept that is also important to understand is that the mine-air diesel-produced CO_2 concentation (background CO_2 subtracted) is a measure of the amount of ventilation per unit of fuel consumed or per unit of output horsepower. Thus, the diesel-produced CO_2 concentration is directly related by equation 1 to the CFM/actual output BHP*.

$$\frac{CFM}{BHP} = \frac{45.18 \times BSFC}{\text{Diesel-produced } CO_2, \text{ \% by Vol.}} \qquad \text{(Eq. 1)}$$

BSFC = Average brake specific fuel consumption, lb/BHP-hr (can vary, .45 lb/BHP-hr is a typical value)

CFM = Volume flow rate of air, CFM

BHP = Brake horsepower produced, BHP

Figure 4 is an illustrative plot of the CFM/BHP versus the diesel produced (CO_2,% - .035) and measured CO_2 concentration (1).

Thus there are at least two important reasons to measure the mine air CO_2 concentrations. One is that they provide direct measures of the CFM/BHP

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* The term "actual ouput BHP" is used to emphasize that the CO_2 measurement is related to the actual power being produced by the vehicle which is different than the "installed" or "rated power" of the engine.

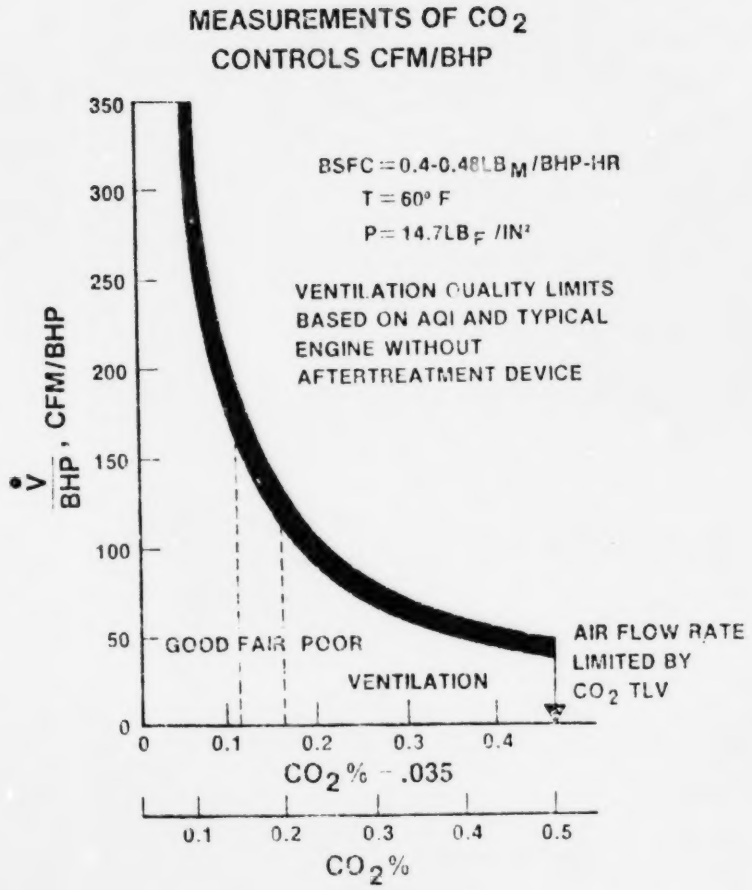


Figure 4. Relationship between ratio of air flow rate to produced BHP and mine air CO_2 concentration.

and the other is that they provide data for determining the slopes of the characteristic curves.

The computer program calculates these and other parameters which are very useful in the interpretation of the results.

Measurements Included in Study

Table 2 briefly describes each of the measurements included in the study. Table 3 lists, on a daily basis, the numbers of measurements of each type made at each location.

As indicated, time-weighted-average (TWA), CO_2, CO, NO, NO_2 and particulate matter measurements were made daily at each of four locations; however, the locations were not the same every day.

The TWA CO_2 and CO concentrations were measured on a sample collected in a 22-litre Calibrated Instruments 5-layer bag over the sampling period and read out at the end by accurately calibrated electronic instruments. The Fuji ZFP5 NDIR portable CO_2 monitor was used to measure CO_2 and the Ecolyzer 2106 portable electrochemical CO monitor with its Purafil interference filter was used to measure CO in the bag. NO_2 and NO are not stable and when stored in a bag for periods greater than a few minutes, significant concentration changes occur. Therefore, they were not measured, as these bags were collected over time periods up to 5 hours.

Palmes' passive samplers were used to measure the NO_2 and NO_X concentations. NO_2 reacts with TEA-coated screens and the reaction products are proportional to the concentration of the NO_2 or NO_X to which the sampler is exposed. For NO_X measurement, NO is converted to an equal volume of NO_2 by a chromic acid disk which is inserted in the NO_2 sampler and in this way the sampler measures the combined ($NO + NO_2 = NO_X$) concentration. The NO_2 concentration is calculated first and is subtracted from the simultaneously-

Table 2. Description of Measurements

Pollutants measured	How measured	Other measurements	
Bag CO & CO_2	Bag samples read out by Ecolyzer 2106 for CO and by Fuji ZFP5 for CO_2	Mode times	Daily record of all load & haul times.
		Air flows	Daily - Recirculation possible (Alnor Velometer)
Palmes NO_2 and NO_X	Palmes NO_2 & NO_X passive samplers	Temperatures	Daily
Particulate (respirable) (Total particulate is collected at 4 L/min without cyclone.)	Pump draws air at 1.7 L/min flow rate through 10 mm nylon cyclone to remove coarse particles, then through 37 mm Gelman A/E glass fiber filter to collect respirable particles.	Fuel Sulfur	Two samples during study
SO_2 SO_4	By calculation from CO_2 concentration, fuel sulfur analysis and assumed 10.0% conversion of fuel sulfur to SO_4; remainder to SO_2.		

Continuous Instruments with Rustrak 288 DC-powered strip chart recorders.

NO - Ecolyzer 2202 For comparison
NO_2 - Ecolyzer 2302 with Palmes' samplers

CO_2 - Fuji ZFP5 to spot check various locations
CO - Ecolyzer 2106

Table 3. Daily Record of Measurements

Date	Location	Time Weighted Average: Bag CO & CO_2	Palmes NO_2 & NO_X	Particulate: Total	Particulate: Resp.	Continuous CO_2, CO, NO, & NO_2
11/26/84	Ups - BO4 near fan	1	2 ea.	2		All
	Truck	1	2 ea.	2		
	Downstream	1	2 ea.	2		
	Drift Wall	1	2 ea.	2		
11/27/84	Ups - #7 drift	1	2 ea.	2		All but CO
	Truck	1	2 ea.	2		
	Loader	1	2 ea.	1*		
	Drift Wall	1	2 ea.	1	1	
11/28/84	Mine intake	1	3 ea.		**	All but CO
	Ups - #7 ext.	1	3 ea.		2	
	Truck	1	3 ea.		2	
	Drift Wall	1	3 ea.		2	
11/29/84	Mine intake	1	3 ea.		2	All but CO
	Ups - #7 ext.	1	3 ea.		2	
	Truck	***	3 ea.		1*	
	Drift Wall	1	3 ea.		2	
11/30/84	Mine intake	1	2 ea.		2	All but CO
	Ups - #7 ext.	1	2 ea.		2	
	Truck	1	3 ea.		2	
	Drift Wall	1	3 ea.		1*	

* One pump stopped
** No samples
*** Punctured bag

measured NO_X concentration to arrive at the NO concentration. More details on this calculation are presented in Appendix II.

Total and respirable particulate matter were collected on 37-mm Gelman A/E glass fiber filters as discussed below. The diesel portion of this particulate matter which is referred to as "respirable combustible dust" (RCD) was determined by measuring the carbon and hydrogen contents of the particulate on the filter using a Perkin Elmer Model 240 Elemental Analyzer. The weight of diesel particulate on a filter is assumed to be equal to the sum of the weights of carbon and hydrogen found on the filter. Such an assumption should be correct in the Lanigan Mine where the ore contains no organic material and there is no drilling with compressed air to produce a drill oil mist that would be collected and respond similarly to diesel particulate in the Perkin Elmer Model 240 Elemental Analyzer.

The SO_2 concentration is calculated from the measured CO_2 concentrations, the fuel sulfur concentration and the assumption that all of the fuel sulfur is combusted to either SO_2 or SO_4. The fraction of this fuel sulfur which is combusted to SO_4 rather than to SO_2 is estimated to be 10% when the exhaust is passed through the catalytic converter and the other 90% is assumed to be SO_2.(5)

Two locations which were monitored all 5 days were 'on-board the truck near the operator position' and 'next to the right-hand wall of BO489 drift about 4 ft above the floor, 40 ft in from the crosscut.' Two other locations had been selected originally for daily monitoring, but changes were made for the reasons discussed below. These were 'on-board the loader' and 'downstream.'

On the first day in addition to the truck and drift wall positions, one sampler was placed 200 ft upstream near the fan intake and the other was

placed 125 ft downstream instead of on the loader which happened to be right beside the wall sampler. However, the first days CO and CO_2 measurements revealed little, if any, differences in any of the four locations. Thus the decision was made to move the upstream sampler from near the fan all the way to #7 drift which was thought to be the only source of fresh air to the loop formed by the intersecting drifts -- #7 extension - B04 - B3165 - P.E.5. Furthermore we decided not to sample the downstream location anymore. This sampler was placed on the loader the second day.

The second days CO and CO_2 readings again indicated that the loader and drift wall samplers were sampling essentially the same concentrations, so it was concluded that sampling the loader was unnecessary and that the sampler could be better used elsewhere. These observed concentration uniformity conditions were, no doubt, due in part to the earlier-mentioned recirculation.

Air flow measurements on the morning of the third day did not detect any flow through #7 drift into the loop at #7 extension. Furthermore, air flow measurements in the other drifts intersecting this loop revealed no significant air movement. However, these relatively large drift dimensions resulted in low, difficult to measure velocities making it difficult to know with certainty that none of the drifts intersecting this loop was providing fresh air to the loop. We did, however, know that the air from #7 extension was being drawn to the fan and blown through the B04/B0489 crosscut. Thus we decided to place our 'upstream' sampling station in #7 extension on each of the last 3 days of the study.

Because of this confusion about the source of air into the section being monitored, we decided to attempt only to distinguish between natural gas emissions in the mine intake air and mine-produced diesel emissions

which hopefully were largely generated in our study area. Thus the loader sampler was moved to the mine 'fresh' air intake location where it was located the last 3 days to monitor intake air propane emissions. Presumably any additional concentrations of the pollutants of concern measured at our other three samplers were of diesel origin.

The continuous instruments for CO_2, NO, NO_2 and CO were placed on a 4 ft high shelf located next to the B0489 drift wall TWA sampling station 40 ft in from the crosscut. These CO_2, NO, and NO_2 readings were recorded each day by Rustrak strip chart recorders. Interference scrubbers supplied by the instrument manufacturer were used on both the NO and NO_2 inlets of the Ecolyzer 7230 instrument. The fourth recorder failed early in the week and it was decided that the continuous CO readings were the least necessary, so CO was not recorded after that. The NO and NO_2 readings are needed to compare the averaged continuous instrument readings with those obtained by the Palmes samplers at the same (drift wall) location over the same time interval. This comparison is to show the differences between the two methods and, if necessary, provide correction factors for the Palmes samplers or for the instruments. One of the objectives of the ongoing Michigan Technological University/U.S. Bureau of Mines diesel emissions research effort is to find other TWA NO_2 and NO_X measurement methods and to compare various NO_2 measurement methods.

Because of concern about the effect of position on our drift wall concentration readings, occasional checks were made during the week. These checks involved carrying one of the continuous instruments (usually NO/NO_2) further into the drift to the loader position. We concluded from these

checks at different positions in the drift that the drift wall position was quite representative of the entire drift. Such concentration uniformity is not found in dead end drifts where diesel-powered load-haul-dump vehicles move into and out of the drift and operate under full-engine-load high-engine-speed conditions to load the bucket, but might be expected in the present situation where the engine idled and there was little vehicle movement.

Auxiliary ventilation consisting of line brattice and blowing tubing was not used during our measurements. The decision not to use auxiliary ventilation was based on our request to monitor worst case concentrations.

Table 3 shows that total particulate was measured the first 2 days only and that respirable particulate was measured the last 3 days of the study. Sampling total particulate involves drawing air through a filter which collects all of the airborne particulate. The flow rate isn't critical as long as it is known and remains constant. Our usual practice is to use as high a flow rate as the pump will handle so that short sampling times will result in a sufficient quantity of diesel particulate for accurate analysis. We used a 4 L/min flow rate for this purpose.

Sampling respirable particulate involves the use of a 10 mm nylon cyclone which impacts the coarse 'nonrespirable' particles in the apex section and only the fine fraction passes by and is collected on the filter. These special cyclones have been characterized and found to produce an acceptable size separation at a 1.7 L/min flow rate (2), so this flow rate is the one commonly used in USA metal-nonmetal mines.

On the first day of the study we observed that huge quantities of salt dust had deposited in some of the filter holder cassettes -- so much that it

began to pour from the cassettes during handling. We guessed that this salt dust was largely 'nonrespirable' and would be removed by using the 10-mm nylon cylones and the standard 1.7 L/min flow rate. Thus we requested that CANMET air freight cyclones to us and these were used during the 3rd, 4th and 5th days of the study. The combination of the cyclones and the reduced flow rates apparently solved the excessive-salt problem since the condition was not observed again during the week.

RESULTS

Mining Conditions for the Study

The measurement data were analyzed by computer to calculate the various parameters discussed here. As already mentioned, we calculate those parameters that will allow us to determine the source of the various pollutants of concern, the reasons for the various concentrations found, which pollutants need to be controlled and the expected effect on the air quality of the recommended control approach. To arrive at these answers for a particular diesel operation requires that we know for the same time period: 1) the concentrations of the pollutants of concern and CO_2 in the fresh air and in the air in the study area, 2) the amount of diesel activity in the study area, and 3) the amount of air flow through the study area. As mentioned above we were unable to identify the source(s) of 'fresh' air to our study area during the various days studied and our 'fresh' air often consisted of air, a portion of which was recirculated air from our study area. We would expect this recirculation over 2-3 miles of large drifts to have at least three effects on the data as follows:

1. The concentrations would build up and decrease slowly since any increase or decrease would require a large volume of exhaust to significantly change the concentration in this very large reservoir of air.

2. Since NO reacts with oxygen in the air to produce NO_2 we would expect the NO_2/NO ratio to be much higher than in a well-ventilated mine area where there is little residence time for the reaction to take place. For the same reason NO in the propane emission should be largely converted

to NO_2 by the time it reaches the study area. Another effect we would expect is the loss of NO_2 by adsorption on surfaces, the effect of which would be lower NO_X concentrations as the air progresses through the mine without receiving any additional influx of NO or NO_2.

3. Our 'upstream' samples were not truly background in the sense of allowing us to assess the diesel impact. Thus the need to use the mine intake values for background corrections.

Table 4 presents the conditions which were measured that were thought to have the greatest effect on the data. Unfortunately, although attempts were made to determine the flow rate of air into the section, the data were not thought to be completely reliable. As a result airflow and CO_2 measurement data needed to arrive at the horsepower of work performed were unavailable. This difficulty in determining the air flow sources and volumes is not uncommon in the face area of mines where day to day changes may have important effects on both flow rates and directions. Thus the evident need for basing control on air quality measurements rather than air flow data alone.

The first two days measurements had indicated that air was coming into the section studied at #7 drift at 50,000 and 40,000 CFM flow rates. We were, however, unable to locate the source of whatever inflows there were during the rest of the week. Air recirculated through the loop formed by #7 extension - BO4 - 33165 and PE5 at about 50,000 CFM throughout the week because the fan upstream of BO489 was "on."

On 11/26/84 the first 26 ft wide pass was being mined. Table 4 shows that we sampled for only about 2 1/2 hours and that the face moved in about

Table 4. Sampling Conditions

Date	Approximate sampling period Time, Start	Stop	Diff., Hrs	Cutting location Pass no.	Depth, ft Start	Stop	Approx. no. of loads	Truck Load time, min Med	Mean	Haul time, min Med	Mean	Est. % of time operating
11/26/84	3:00	5:30	2 1/2	1	70	100	15	3.52	3.72	1.12	4.38	57
11/27/84	12:00	5:45	5 3/4	1	155	190	15	3.12	3.13	1.32	6.75	45
11/28/84	3:00	7:00	4	2	35	80	28	2.78	3.25	0.78	3.43	53
11/29/84	10:30	4:30	6	2	120	190	40	2.92	5.17	1.00	3.37	46
11/30/84	11:00	2:30	3 1/2	1	210	230	28	3.05	4.60	1.47	1.55	74

Fuel properties
Fuel sulfur - 0.0177% by mass

30 ft (from the 70-ft to the 100-ft location). Table 4 also shows that truck loading times averaged 3.7 minutes and hauling times about 4.4 minutes; the median loading time was only 3.52 minutes, not far from the average, but the median hauling time was 1.12 minutes, much lower than the average. We have assumed (as our experience has shown) that the median time is near the time it actually takes to load or to haul. The average, of course, is the time actually taken (on the average) which includes downtime for various reasons. Thus we estimate the percentage of time the truck was loading and hauling as (median time/average time) x 100 as shown in the right hand column of Table 4. We see that on 11/26/84 this amounted to only 57% of the time. Figure 5 illustrates the situation on 11/26/84.

One unusual condition on 11/26/84 was the presence of the diesel-powered bolter prior to the beginning of the cutting operation. Continuous instrument measurements in BO489 while the bolter was operating showed CO_2 - .19%, CO - 7 ppm, NO_2 - 3.8 ppm and NO - 8 ppm. These high NO and NO_2 values, no doubt, had some effect on our first days readings during cutting, loading and hauling due to the earlier mentioned slowly changing concentrations in the loop formed by #7 extension, BO4, 33165, and P.E.5.

We also see that the sampling time was shorter on 11/26/84 than on the other days.

Figure 6 through 9 and Table 4 show that on the first and second days the first pass cut (about 26 ft wide) was completed. On the third day the second pass cut (overall width now about 47 ft) was started, and this was continued the 4th day. On the fifth day a center pass was cut. On the first four days the percentage of time that loading and hauling occurred was in the 45-60% range. This increased significantly to 74% on the last day.

Date - 11/26/84
Drift - B0489

Sampler
Stations:

1. Upstream
2. Truck
3. Downstream
4. Wall

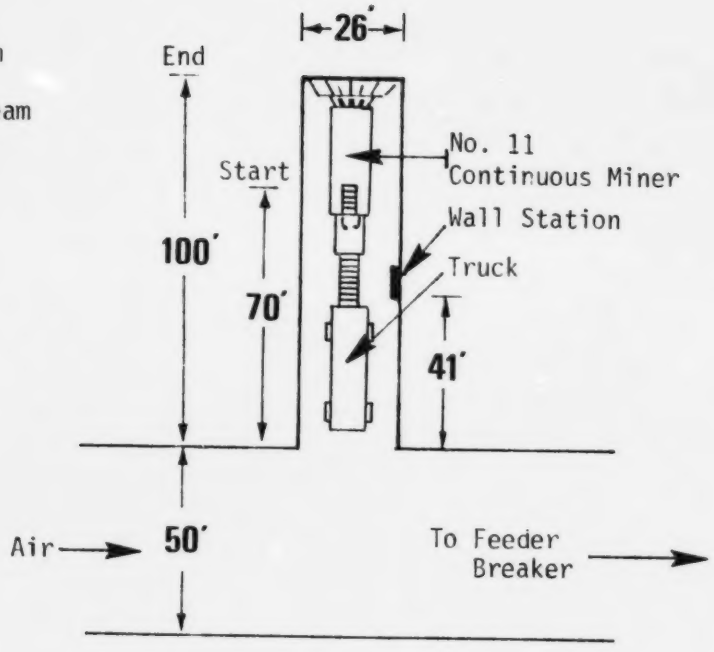


Figure 5. Conditions on 11/26/84.

The fuel sulfur analysis for the week of the study measured by CANMET was found to be 0.0177% by mass. This .0177% value which was later substantiated by a second sample and repeat analysis is extremely low. Typically the fuel sulfur ranges between about .10 and .50% with some no. 1 fuels about .05% by mass. We requested, but were unable to get more detailed information from PCS Mining about the source of the fuel. The effect of such low fuel sulfur contents (as demonstrated in the results of this study) is to significantly improve the air quality index (AQI). In this regard, it will be important for PCS Mining personnel to remain cognizant of the fact that the conclusions are based on the particular fuel sulfur content and different conclusions would apply if the fuel sulfur content were to change. The effect of higher fuel sulfur contents would be especially important in the PCS Mining Lanigan Division where PTX catalytic converters are used for carbon monoxide control. Such converters have been found to convert part of the SO_2 to SO_4 which has more stringent limits in addition to having a more severe effect on the AQI since sulfate emissions contribute to the particulate emissions.

Using our recently-developed data analysis methodology, we assume that load-cycle differences are "averaged out" by taking data over a 4-day period and using the characteristic curve approach to data analysis.

The continuous NO and NO_2 measurements in the drift by the Ecolyzer NO and NO_2 electrochemical instruments were compared with the Palmes' samplers the differences found are listed in the Appendix II. We developed separate correction factors for NO and NO_2 by dividing the time-weighted-average Palmes sampler values by the simultaneously-measured instrument values (drift only) and averaging these. The Palmes' sampler values obtained from all the locations sampled were corrected by multiplying by these correction factors.

Sampler
Locations:

1. Upstream
2. Truck
3. Loader
4. Wall

Date - 11/27/84
Drift - B0489

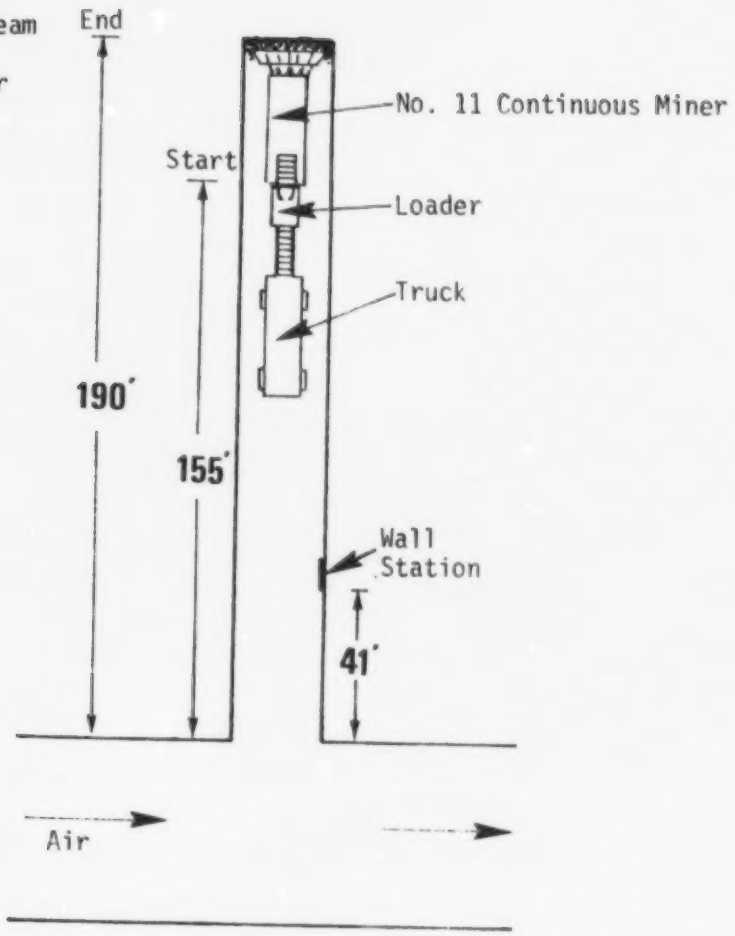


Figure 6. Conditions on 11/27/84.

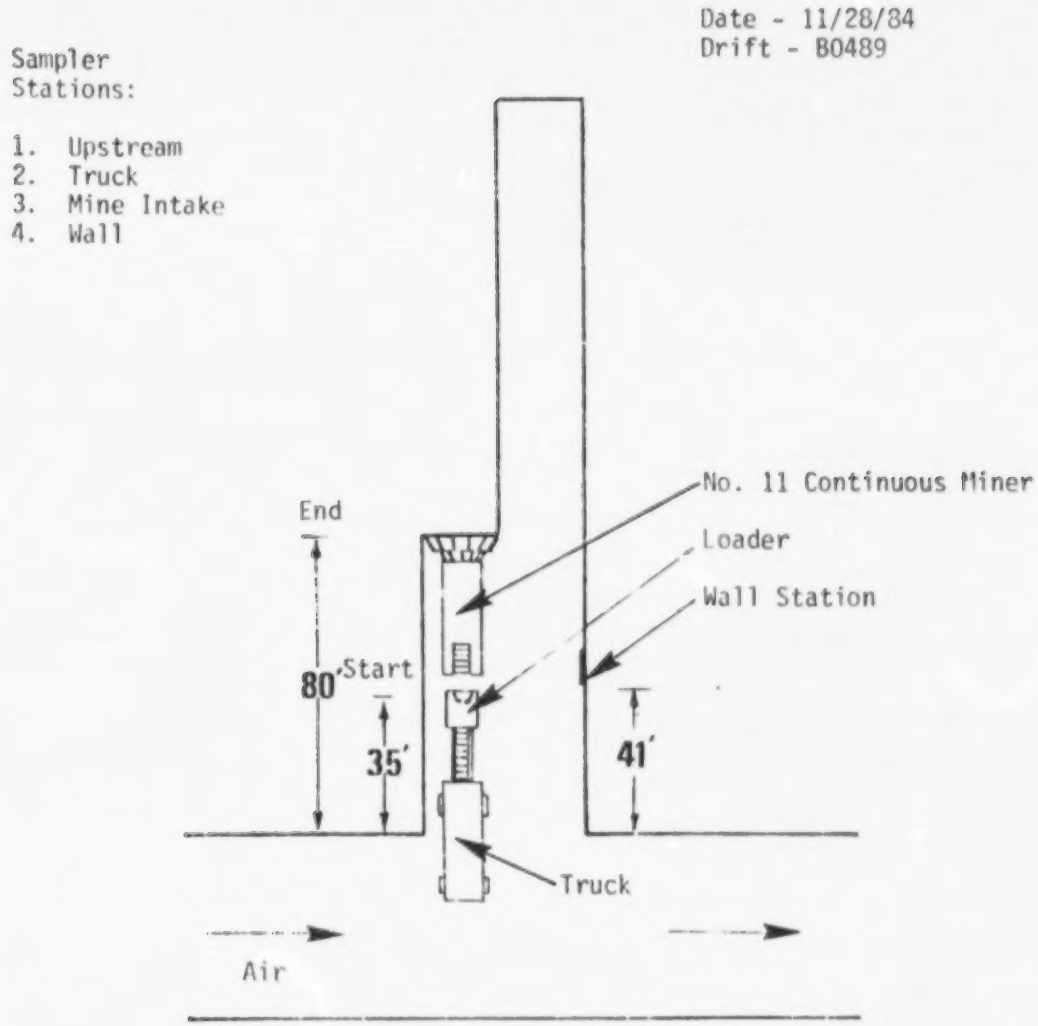


Figure 7. Conditions on 11/28/84.

Sampler
Stations:

1. Upstream
2. Truck
3. Mine Intake
4. Wall

Date - 11/29/84
Drift - B0489

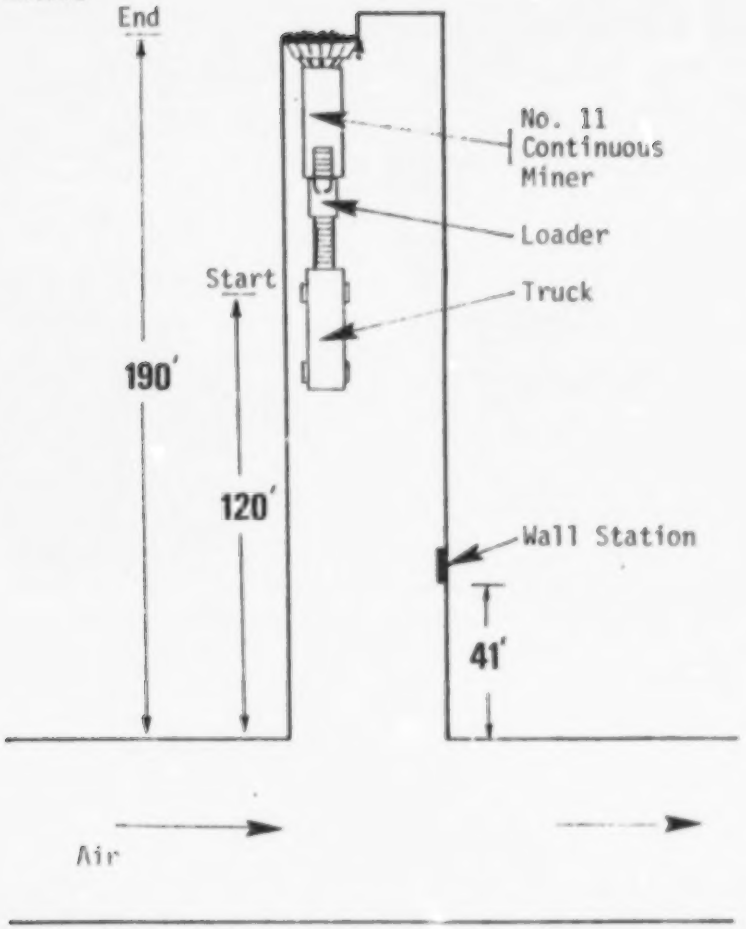


Figure 8. Conditions on 11/29/84.

Date - 11/30/84
Drift - B0489

Sampler
Stations:

1. Upstream
2. Truck
3. Mine Intake
4. Wall

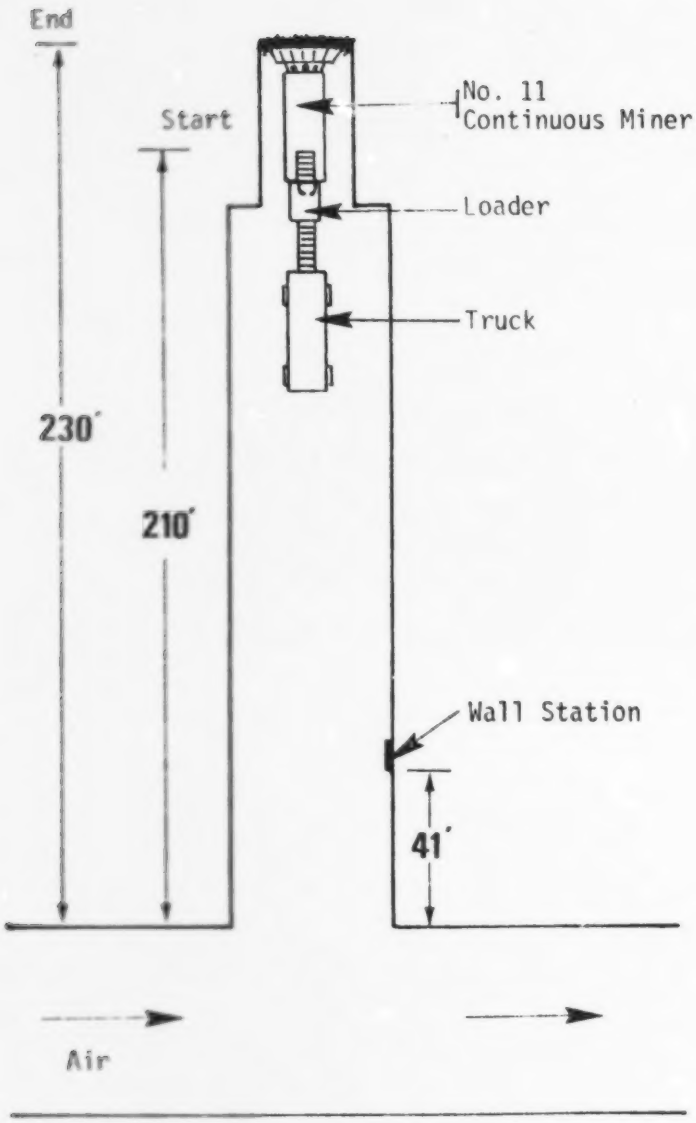


Figure 9. Conditions on 11/30/84.

The data analysis makes use of the Air Quality Index (AQI) which was calculated as follows:

$$AQI = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + 1.5\left[\frac{SO_2}{3} + \frac{RCD}{2}\right]^{*} \qquad \text{(Eq. 2)}$$

$$+ 1.2\left[\frac{NO_2}{3} + \frac{RCD}{2}\right]^{**}$$

where

AQI = Air Quality Index

CO = CO concentration, ppm

NO = NO concentration, ppm

RCD = Respirable combustible dust (particulate)*** concentration & sulfate, mg/m^3

SO_2 = SO_2 concentration, ppm

NO_2 = NO_2 concentration, ppm

*If SO_2 is less than 25% of its TLV the complete bracketed term is set equal to zero in the new AQI calculation; use 0 in place of '25% of TLV' for old AQI calculation.

**If NO_2 is less than 25% of its TLV the complete bracketed term should be set equal to zero in the new AQI calculation; use 0 in place of '25% of TLV' for old AQI calculation.

***Respirable combustible dust is diesel particulate determined by the methods described.

Note that the new air quality index has been modified to use the more recent recommendations for dealing with the bracketed terms (6). In the old AQI these were set equal to zero only when the SO_2 and NO_2 values were zero. The new AQI sets these equal to zero when SO_2 and NO_2 are less than 25% of their ACGIH TLVs. For SO_2 this limiting value is now 2 ppm x .25 = 0.50 ppm and for NO_2 it is 3 ppm x .25 = 0.75 ppm.

Data Analysis

Based on the earlier mentioned considerations, the analysis that follows is for the truck and the B0489 drift wall sampling stations. The mine intake air data is used to determine the background effect.

In the data analysis we subtract the background concentrations when we want to evaluate the effect of the diesel only such as in the determination of the slopes of the characteristic curves. However, we use the actual readings which also include the background effect when we are determining compliance with the various assumed limits (note that some of the assumed limits are legally-enforced limits).

Table 5 presents the actual measured pollutant concentrations from the truck, B0489 drift wall, upstream and mine intake. The CO_2 weekly averages of .173% for the truck and .170% for the drift wall reveal the similarity between the two and even the .153% CO_2 in the 'upstream' air, which as discussed earlier is partly recirculated air, is not much different than that on board the truck or in the drift.

The mine intake CO_2 concentrations which are mainly due to propane burning remain in the .11 to .13% range while CO and NO seems to vary a little more. Part of this variation is no doubt related to imprecision in the Palmes samplers.

Table 5. Average Daily Concentrations - Truck, Drift Wall, Upstream, and Mine Intake

Date monitored	Location	CO_2, %	CO, ppm	NO, ppm	NO_2, ppm	SO_4, mg/m^3	SO_2, ppm	TPM,** mg/m^3	TRPM,** mg/m^3	RCD, mg/m^3	*** OLD AQI	*** New AQI
						Truck						
11/26/84	BO489-BO4	0.160	6.0	2.7	3.0	.01	.03	31	-	1.01	3.34	2.55
11/27/84	BO489-BO4	0.162	5.1	1.1	1.1	.01	.03	22	-	0.56	1.67	1.21
11/28/84	BO489-BO4	0.162	7.0	2.2	1.2	.01	.03	-	2.31	0.69	2.01	1.48
11/29/84	BO489-BO4	*	*	1.8	1.0	-	-	-	3.21	0.50	-	-
11/30/84	BO489-BO4	0.210	5.5	5.8	1.6	.03	.07	-	3.60	1.08	3.10	2.20
Avg.		0.173	5.9	2.7	1.6	.02	.04	27	3.04	0.77	2.34	1.74
						Drift Wall						
11/26/84	BO489	0.150	5.0	2.4	1.5	.01	.02	353	-	2.9	6.28	4.06
11/27/84	BO489	0.155	4.8	1.6	0.84	.01	.02	15.1	2.1	0.45	1.37	1.00
11/28/84	BO489	0.150	6.0	2.7	0.64	.01	.02	-	14.1	0.17	0.83	0.32
11/29/84	BO489	0.190	5.0	4.5	0.80	.02	.05	-	5.2	0.59	1.75	1.27
11/30/84	BO489	0.205	5.5	5.7	1.3	.03	.07	-	9.3	2.60	5.69	3.75
Avg.		0.170	5.3	3.4	1.0	.02	.04	184	7.7	1.34	3.18	2.14

* Punctured sample bag
** TPM = total particulate matter, TRPM = total respirable particulate matter.
*** Old AQI includes bracketed terms where SO_2 and NO_2 > 0;
New AQI includes bracketed terms only if SO_2 and NO_2 > 25% of TLV.

Table 5 Continued. Average Daily Concentrations - Truck, Drift Wall, Upstream, and Mine Intake

Date monitored	Location	CO_2, %	CO, ppm	NO, ppm	NO_2, ppm	SO_4, mg/m^3	SO_2, ppm	TPM,** mg/m^3	TRPM,** mg/m^3	RCD, mg/m^3	*** OLD AQI	*** New AQI
						Upstream						
11/26/84	BO4	.150	5.0	3.5	4.0	.01	.02	2.3	-	.43	2.65	2.32
11/27/84	#7 Drift	.138	4.4	2.7	0.65	.01	.01	1.4	-	.29	1.00	0.35
11/28/84	#7 Ext.	.165	7.0	3.9	1.6	.01	.03	-	.54	.26	1.44	1.23
11/29/84	#7 Ext.	.162	3.5	1.6	1.0	.01	.03	-	.97	.30	1.12	0.88
11/30/84	#7 Ext.	.150	3.5	1.9	0.86	.01	.03	-	3.1	.25	0.98	0.78
Avg.		.153	4.7	2.7	1.6	.01	.02	1.9	1.5	.30	1.44	1.18
						Mine intake						
11/26/84	Intake	-	-	-	-	-	-	-	-	-	-	-
11/27/84	Intake	-	-	-	-	-	-	-	-	-	-	-
11/28/84	Intake	.122	3.5	1.6	.69	.00	.00	-	-	-	-	-
11/29/84	Intake	.126	1.5	1.7	.78	.00	.00	-	1.5	0.00	.41	.41
11/30/84	Intake	.112	1.6	.63	.60	.00	.00	-	1.5	0.07	.37	.09
Avg.		.120	2.2	1.3	.69	.00	.00	-	1.5	0.04	.41	.12

* Punctured sample bag
** TPM = total particulate matter, TRPM = total respirable particulate matter.
*** Old AQI includes bracketed terms where SO_2 and NO_2 > 0;
New AQI includes bracketed terms only if SO_2 and NO_2 > 25% of TLV.

The calculated SO_2 and SO_4 concentrations are very low at all four locations for all five days as a result of the low fuel sulfur content.

Total particulate matter concentrations (TPM which is combined respirable and nonrespirable) were measured only on the first two days. These TPM values are seen to be very high for the truck and drift wall locations. The 353 mg/m^3 measured on the drift wall is 35 times the ACGIH TLV, of 10 mg/m^3, the limit that has also been proposed for Saskatchewan. The 31 and 22 mg/m^3 truck TPM readings are 3.1 and 2.2 times the proposed standard. The truck total respirable particulate matter (TRPM) was however, below the 5 mg/m^3 ACGIH TLV. The drift wall TRPM exceeded 5 mg/m^3 on two out of four days.

As mentioned earlier we had requested that no auxiiary ventilation be used in the drift so that worst case diesel emissions concentrations would occur allowing us to get improved accuracy in the sampling times available. This decision is, no doubt, responsible in part for the high drift dust concentrations. For example, upstream TRPM was well below the 5 mg/m^3 limit.

Drift wall NO_2 readings remained below the limit during all 5 days. Diesel particulate (RCD) in the drift was however, above the 2 mg/m^3 limits (assumed) on the first and last day. Likewise the AQI in the drift was above the assumed limit of 4 on the first and last day.

Two NO_2 readings exceeded the Sasketchewan limit of 2.0 ppm. These were the 4.0 ppm upstream reading and 3.0 ppm truck reading, both measured on the first day. These high readings were probably in part a result of the roof bolter which moved out just prior to our measurements. Single drift NO and NO_2 measurements with the Ecolyzer 7230 during bolting had given values

of 8.0 and 3.8 ppm respectively. Such high NO and NO_2 readings were not recorded on the other days during loading and hauling operations.

Table 5 also indicates that virtually no RCD can be measured in the propane emissions as measured in the mine intake air during the last two days. RCD was also relatively low in the 'upstream' and truck measurements.

Table 6 presents the truck and drift concentrations with the background (mine intake) values subtracted to give the 'diesel-produced' concentrations. These background-corrected truck CO_2 values are seen to be uniform at about .04% the first three days, but to more than double to .098% the fifth day. The 4th day's sample was lost due to a punctured sample bag. Drift CO_2 values are also uniform at about .03% the first three days, about double at .064% the 4th day and triple at .093% the last day. These differences can be accounted for only in part by differences in the operating conditions recorded (Table 4). As mentioned earlier, air flow data are unreliable and may account for a large part of the observed day to day differences. The background-corrected NO and NO_2 values in Table 6 don't correlate with the CO_2 data as well as we'd like and we suspect this is due to Palmes sampler imprecision. CO follows quite well in most cases, but doesn't increase with CO_2 the last day. RCD is somewhat more variable giving higher readings the first and last day.

Figures 10 through 19 are the pollutant characteristic curves. These curves, as discussed earlier, were developed by the procedure presented in Appendix I. The slopes are tabulated in Table 7. Each value presented in Table 7 is a pollutant/CO_2 ratio (background subtracted) for that day. For example, if we take the first CO and CO_2 values for the truck from Table 6

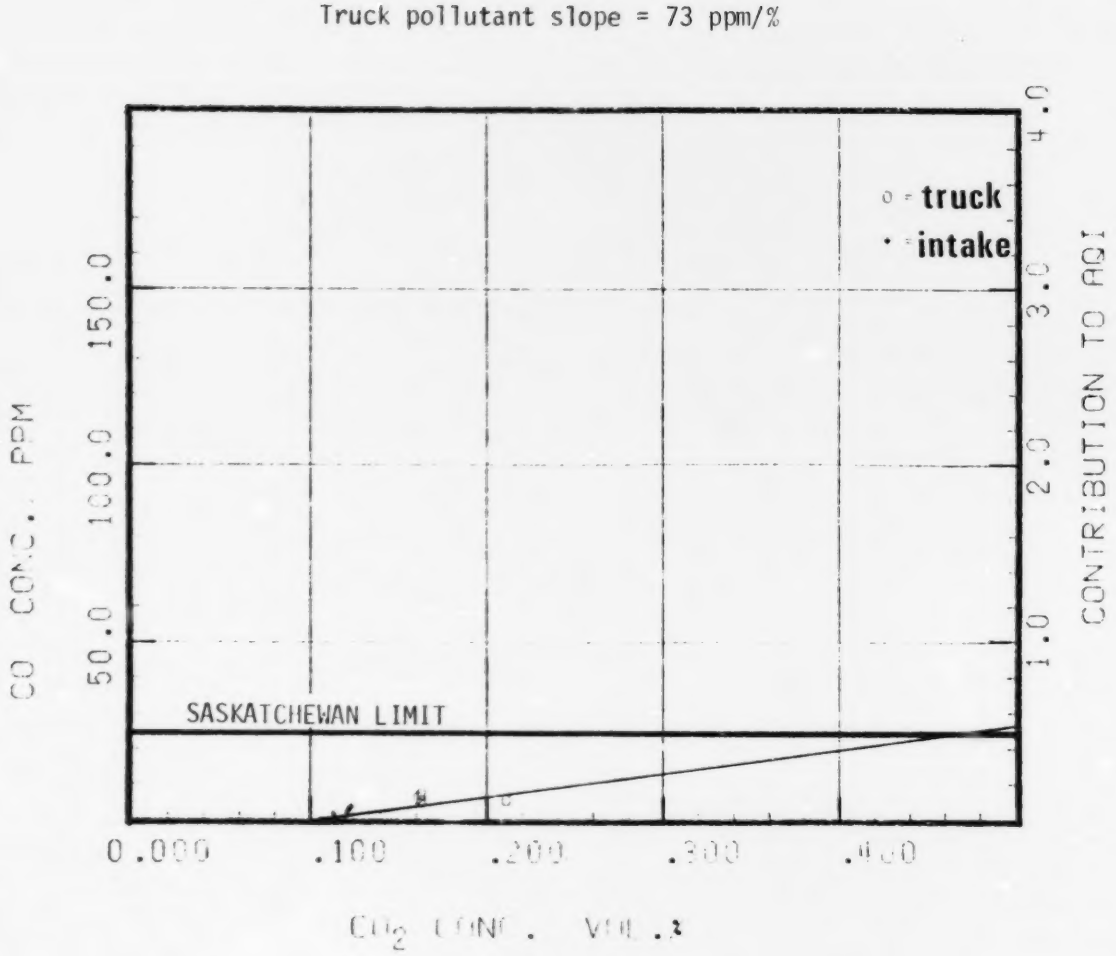


Figure 10. CO characteristic curve for Truck, November 26-30, 1984.

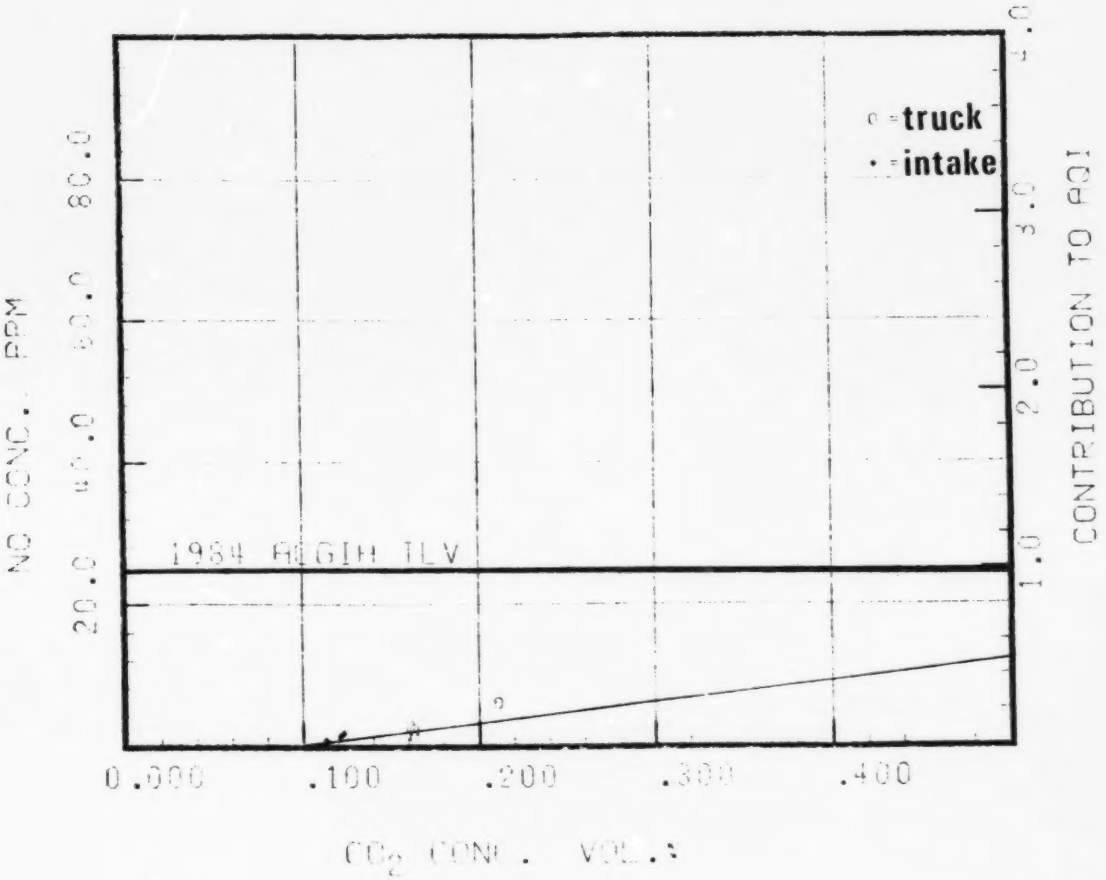


Figure 11. NO characteristic curve for truck, November 26-30, 1984.

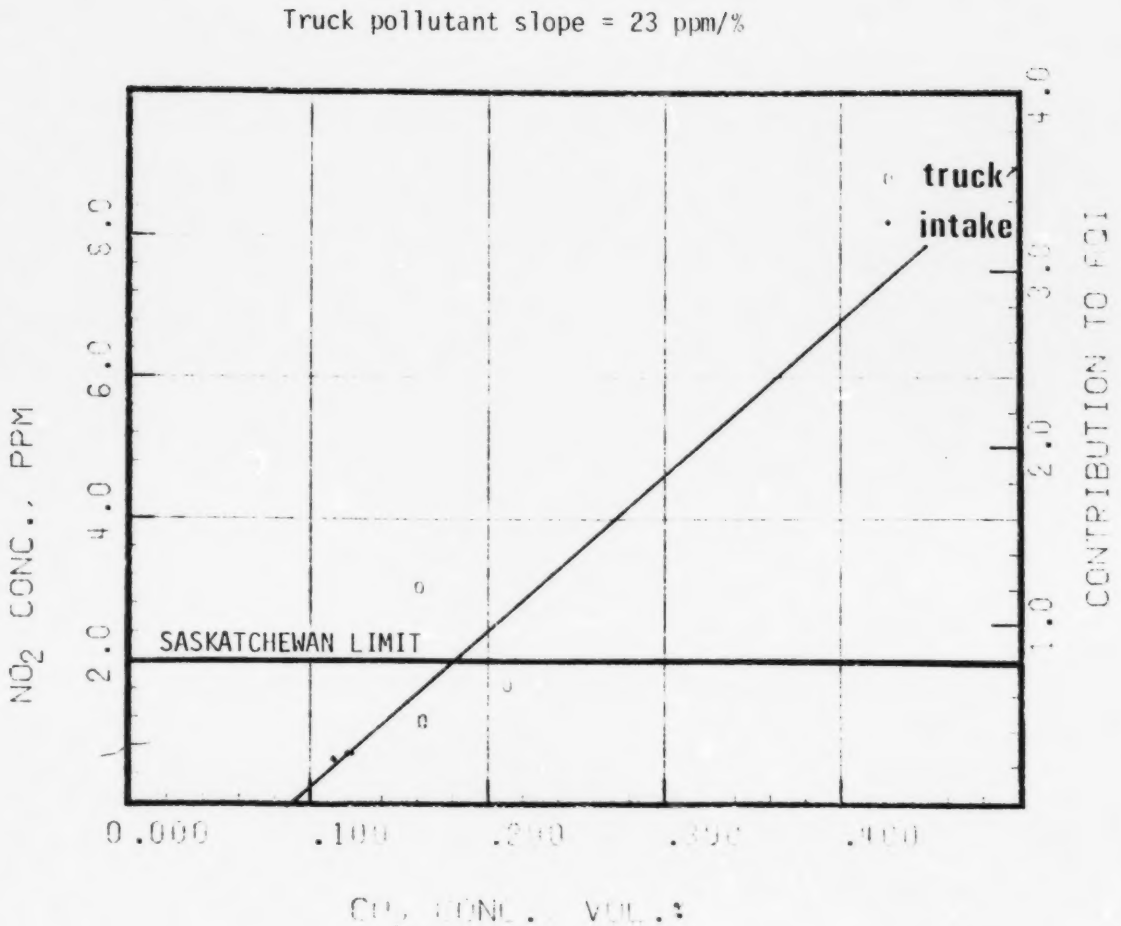


Figure 12. NO_2 characteristic curve for truck, November 26-30, 1984.

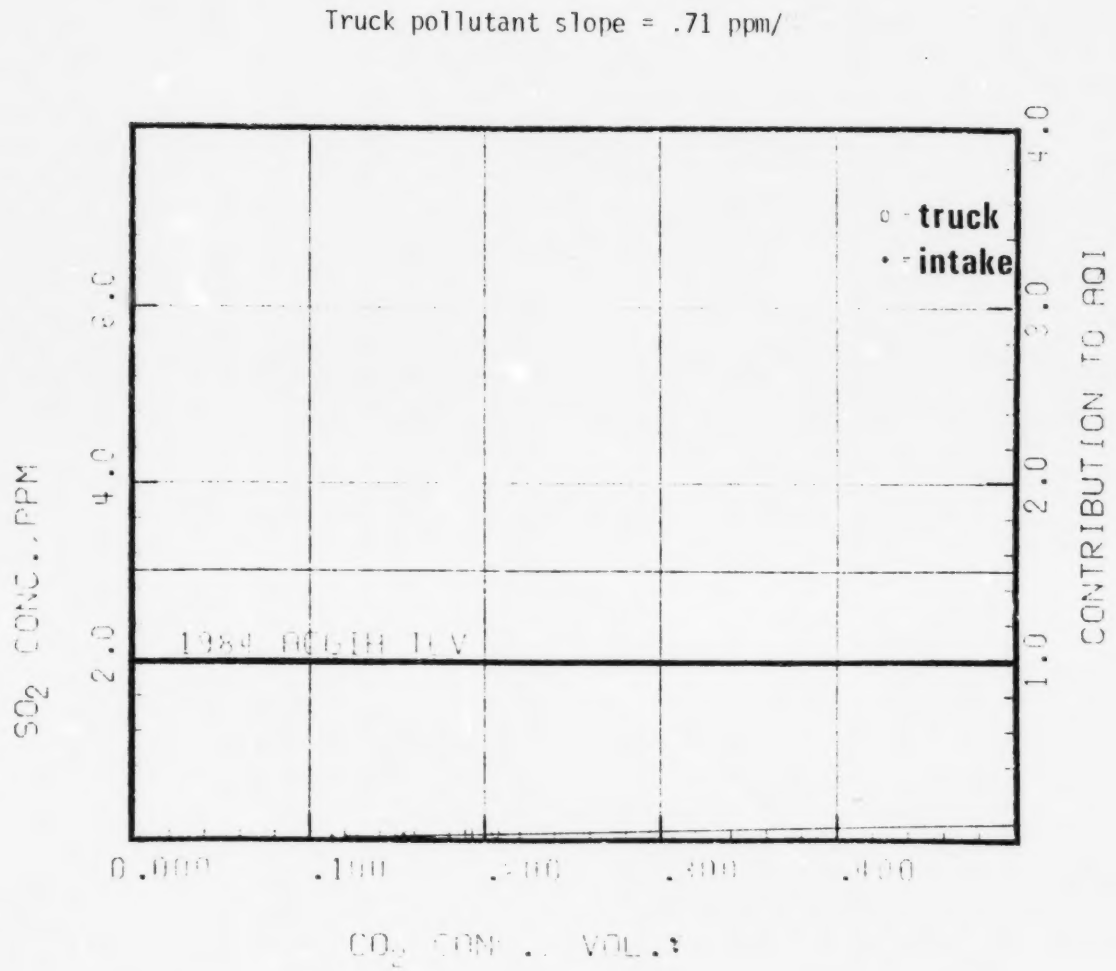


Figure 13. SO_2 characteristic curve for truck, November 26-30, 1984.

Truck pollutant slope = 16.3 mg/m^3/%

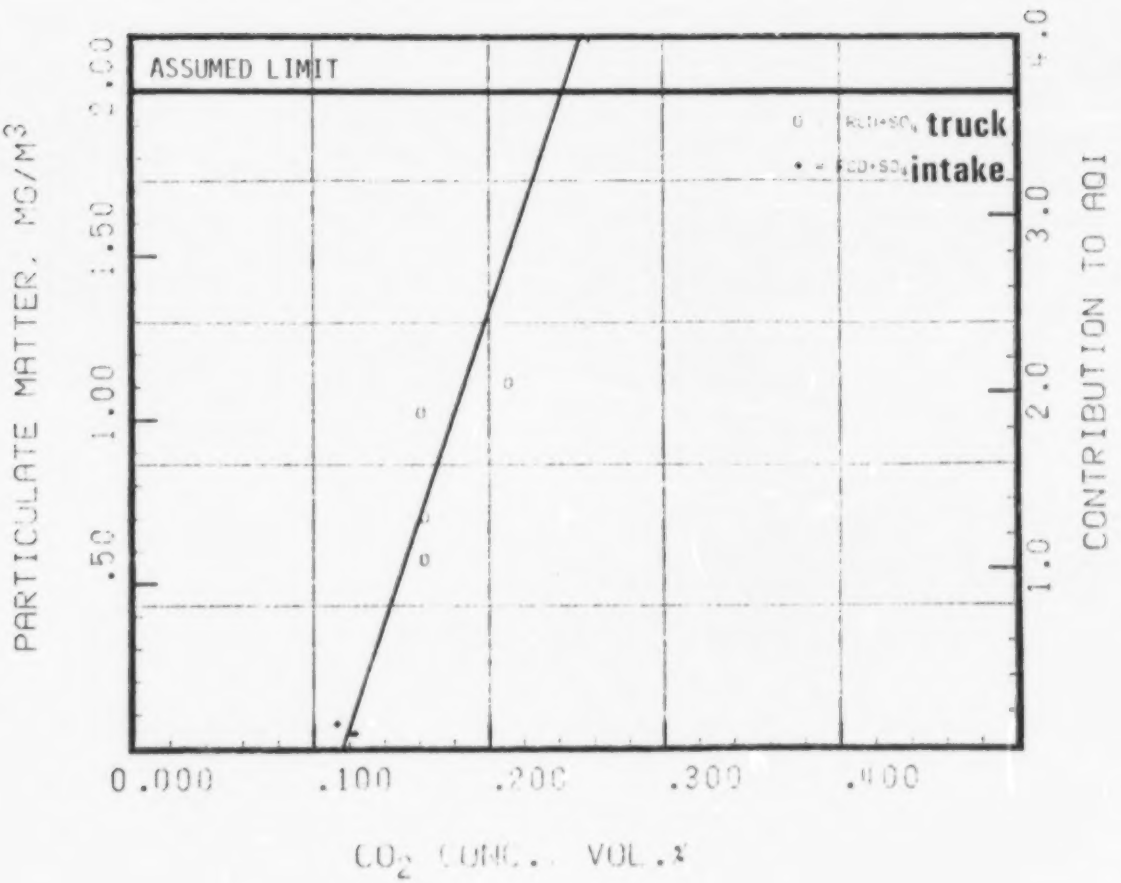


Figure 14. Particulate matter characteristic curve for truck, November 26-30, 1984.

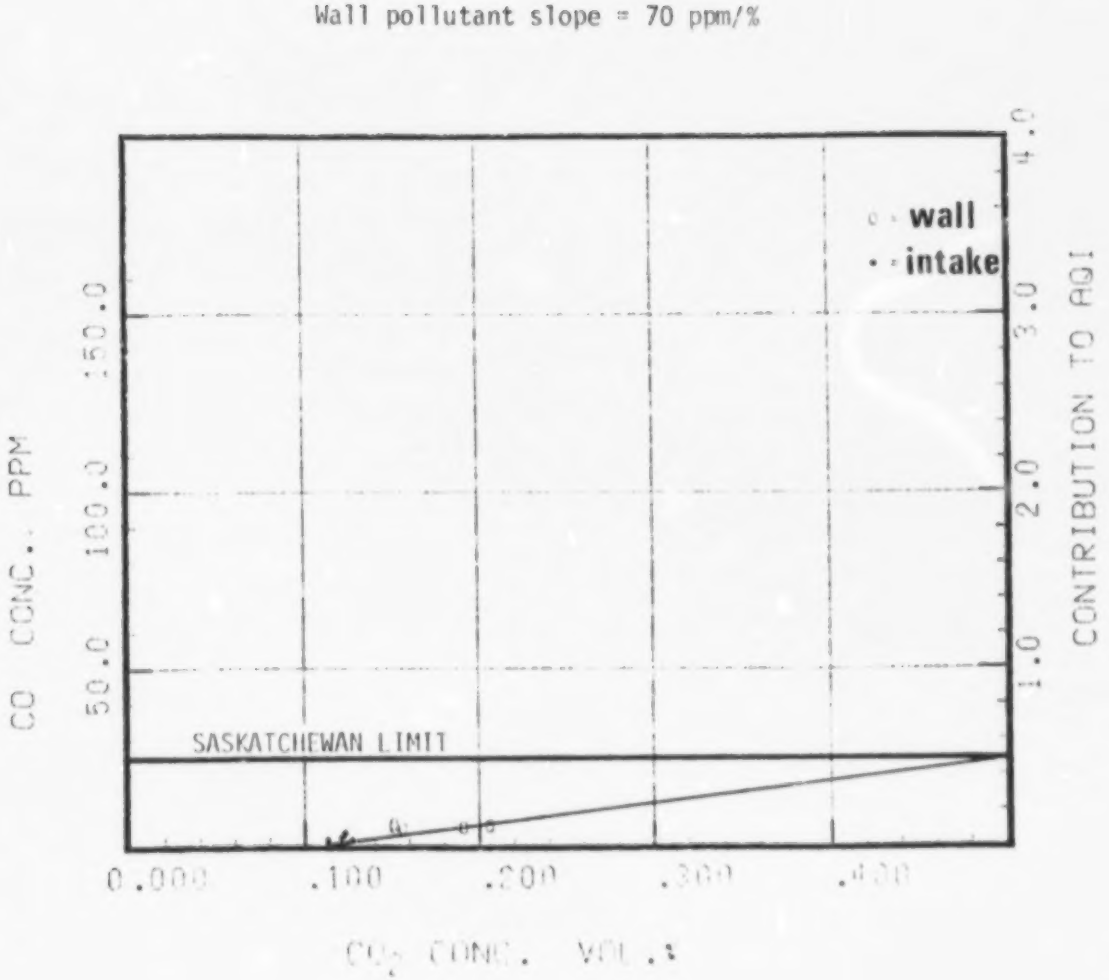


Figure 15. CO characteristic curve for wall, November 26-30, 1984.

Wall pollutant slope = 37 ppm/%

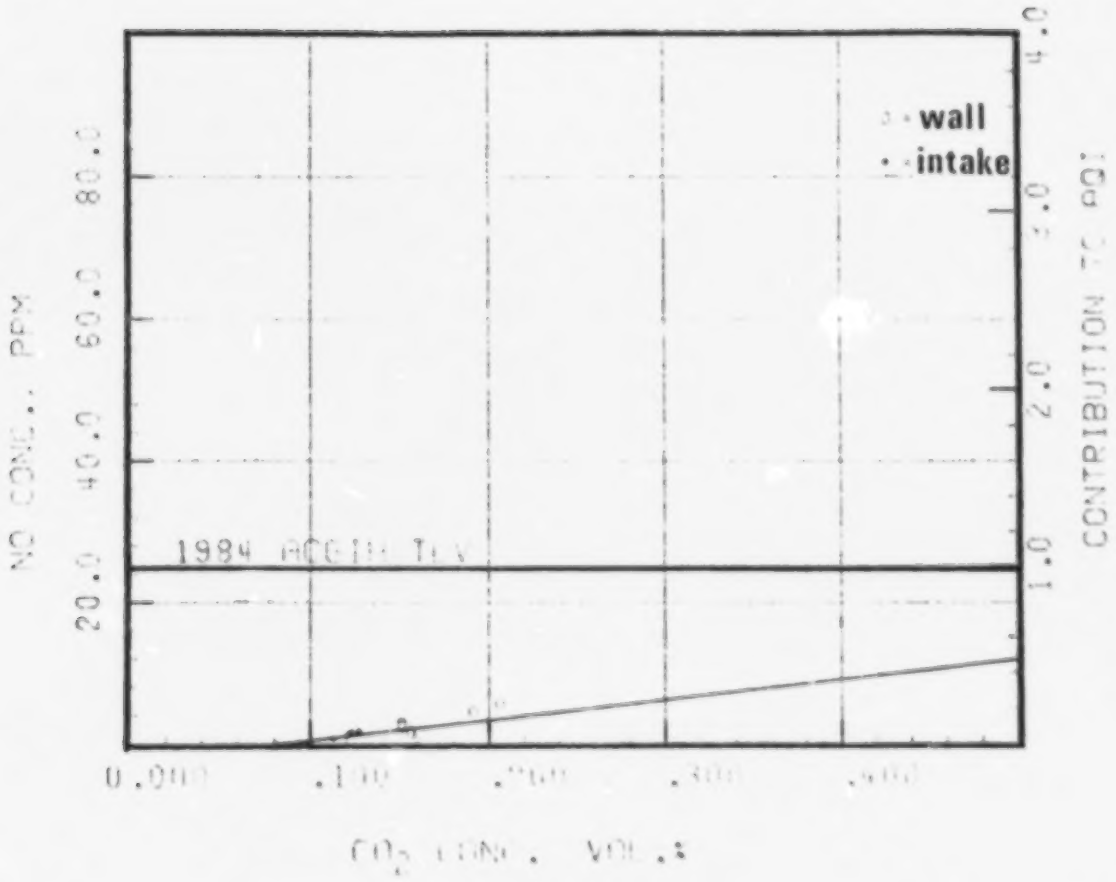


Figure 16. NO characteristic curve for wall, November 26-30, 1984.

Wall pollutant slope = 9.6 ppm/%

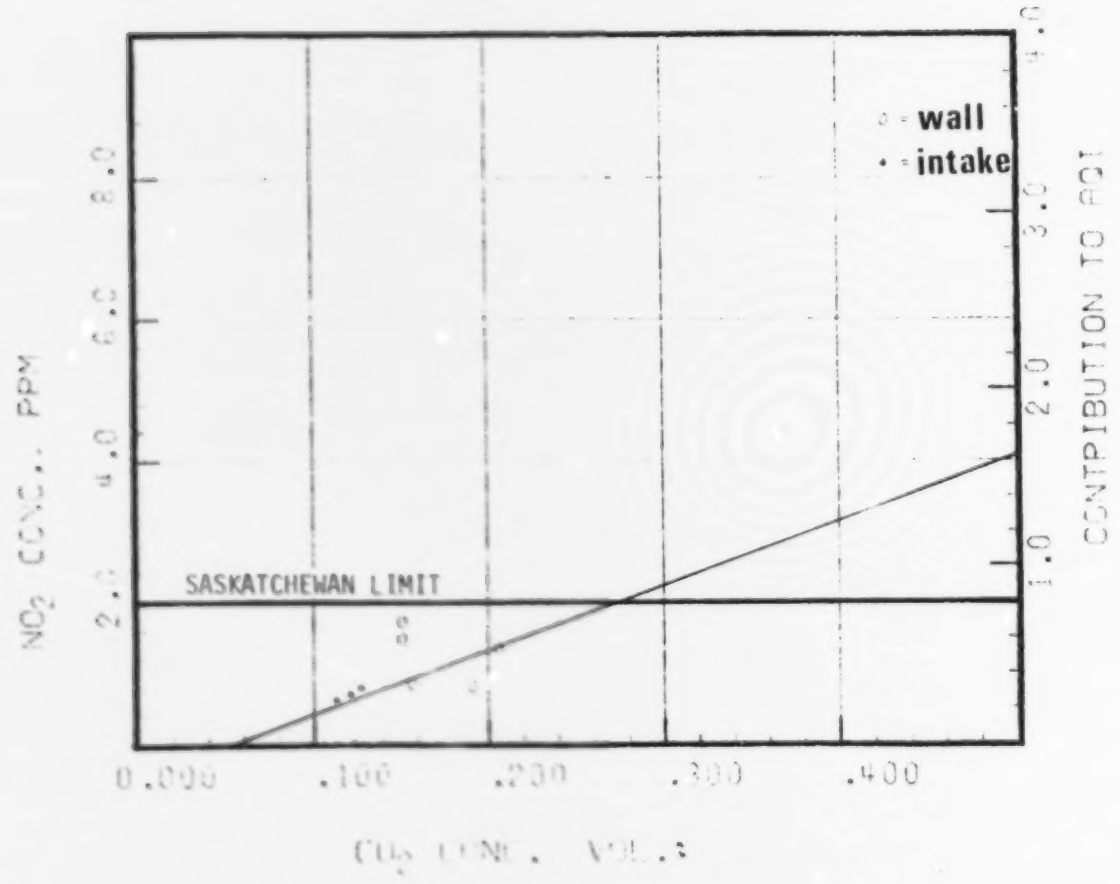


Figure 17. NO_2 characteristic curve for wall, November 26-30, 1984.

Wall pollutant slope = 0.71 ppm/%

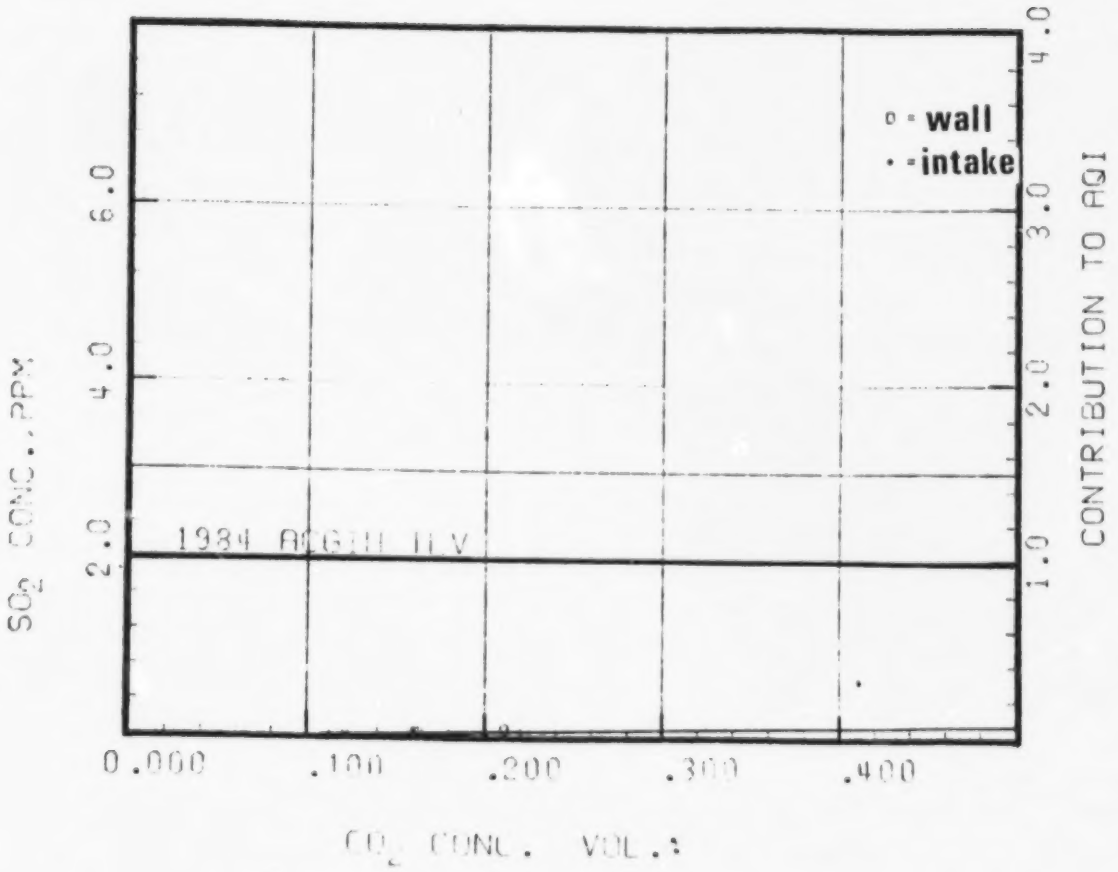
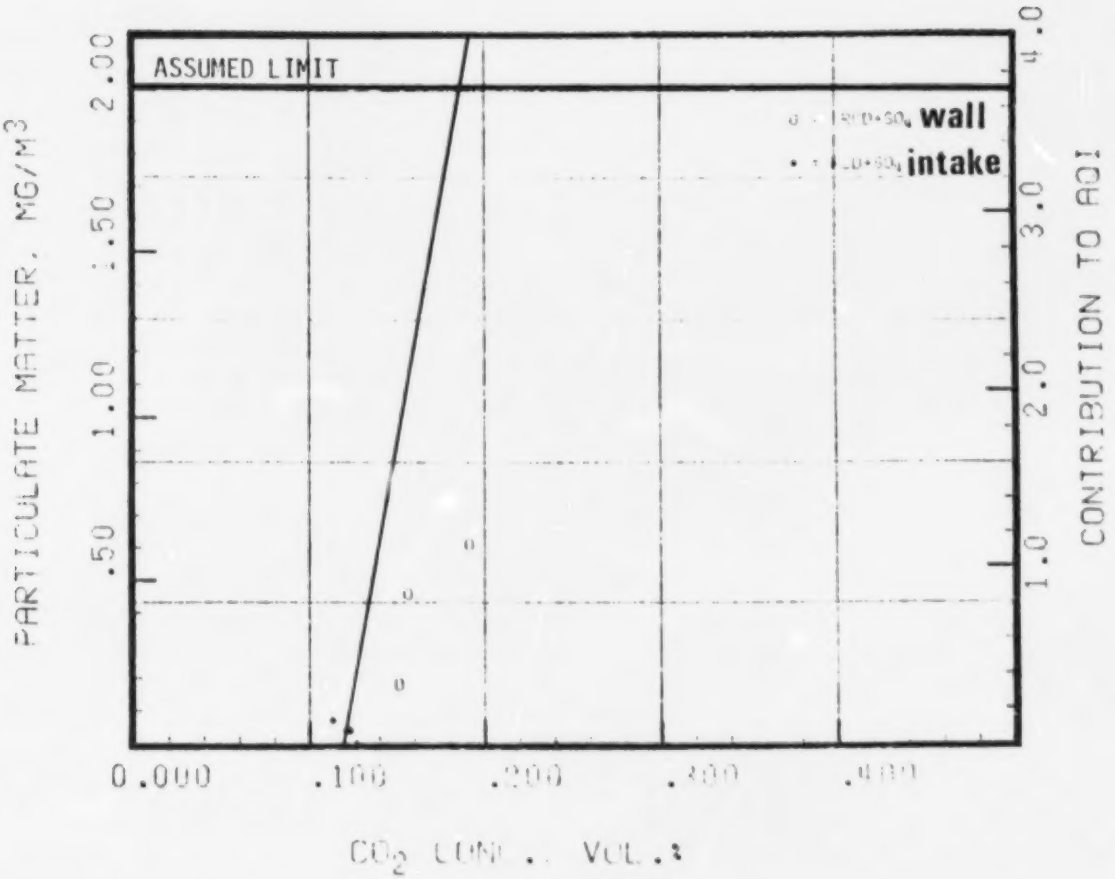


Figure 18. SO_2 characteristic curve for wall, November 26-30, 1984.

Wall pollutant slope = 30 mg/m^3



* NOTE: 2 points outside the coordinate system presented:
RCD + SO_4 = 2.9 mg/m^3, CO_2 = 0.150
RCD + SO_4 = 2.6 mg/m^3, CO_2 = 0.205

Figure 19. Particulate matter characteristic curve for wall, November 26-30, 1984.

Table 6. Absolute Concentration Differences; Truck & Drift Wall

Date monitored	Location	CO_2, %	CO, ppm	NO, ppm	NO_2, ppm	SO_4, mg/m^3	SO_2, ppm	TRPM, mg/m^3	RCD, mg/m^3	TRPM -RCD, mg/m^3	OLD AQI	NEW AQI
Truck - mine intake												
11/26/84*	BO489-BO4	.040	3.8	1.4	2.3	0.01	0.03	-	-	0.97	2.90	1.64
11/27/84*	BO489-BO4	.042	2.9	-	0.43	0.01	0.03	-	-	0.52	-	-
11/28/84	BO489-BO4	.040	3.5	0.61	0.47	0.01	0.03	0.86	0.20	0.66	1.53	0.43
11/29/84	BO489-BO4	-	-	0.04	0.22	--	-	1.76	1.26	0.50	-	-
11/30/84	BO489-BO4	.098	3.9	5.2	1.05	0.03	0.07	2.15	1.14	1.01	2.67	1.85
Avg.		.053	3.7	1.4	0.90	0.02	0.04	1.59	0.86	0.73	1.90	1.32
Drift wall - mine intake												
11/26/84*	BO489	.030	2.8	1.1	0.77	0.01	0.02	-	2.92	-	5.84	3.63
11/27/84*	BO489	.035	2.6	0.27	0.15	0.01	0.02	0.68	0.42	0.26	0.93	0.28
11/28/84	BO489	.028	2.5	1.2	-	0.01	0.02	12.66	0.13	12.53	-	-
11/29/84	BO489	.064	3.5	2.8	0.02	0.02	0.05	3.75	0.59	3.17	1.34	0.49
11/30/84	BO489	.093	3.9	5.1	0.75	0.03	0.07	7.87	2.48	5.39	5.26	3.34
Avg.		.050	3.1	2.1	0.33	0.02	0.04	6.20	1.30	4.90	2.74	0.83

* Mine intake values assumed to be the average for the week.

Table 7. Slopes of pollutant characteristic curves

Date Monitored	Location	CO, ppm/%	NO, ppm/%	NO_2, ppm/%	SO_4, mg/m^3/%	SO_2, ppm/%	TRPM, mg/m^3/%	RCD, mg/m^3/%	TRPM-RCD, mg/m^3/%	OLD AQI/%	NEW AQI/%
				Truck - mine intake							
11/26/84	BO489-BO4	95	34	58	.33	.71	-	24	-	73	41
11/27/84	BO489-BO4	69	-	10	.33	.71	-	13	-	-	-
11/28/84	BO489-BO4	88	15	12	.33	.71	21	16	5.0	38	11
11/29/84	BO489-BO4	-	-	-	-	-	-	-	-	-	-
11/30/84	BO489-BO4	40	53	11	.33	.71	22	10	12.0	27	19
Avg.		73	34	23	.33	.71	21.5	16	8.5	42	25
				Drift wall - mine intake							
11/26/84	BO489	93	36	26	0.33	0.71	-	97	-	195	121
11/27/84	BO489	73	8	4	0.33	0.71	19	12	7	27	8
11/28/84	BO489	89	42	-	0.33	0.71	452	5	447	-	-
11/29/84	BO489	55	43	0.3	0.33	0.71	59	9	49	21	8
11/30/84	BO489	42	55	8	0.33	0.71	85	27	58	57	36
Avg.		70	37	9.6	0.33	0.71	154	30	140	67	17

which are 3.8 ppm and .040% respectively we arrive at the CO/CO_2 ratio of 95 ppm/%, the first value listed in Table 7. These ratios are averaged for the week to arrive at the slope of the characteristic curve which would be expected to pass through the origin when the background values are subtracted (a zero value for diesel-produced CO_2 means the engine isn't operating so no other diesel tailpipe emissions would be produced). We then construct a curve with the same slope passing through the average background pollutant and CO_2 concentration for the week. Figures 10 through 19 are the characteristic curves for the various pollutants. Each days actual truck and drift concentrations are then plotted on the coordinates and we see that the points generally lie about the characteristic curves. Further details of the procedure are presented in Appendix I.

The assumed limits have been imposed on all the characteristic curves as straight horizontal lines. We can express each days pollutant concentration (operating concentration) as a percentage of this assumed limit. Table 8 presents these values for the on-board truck and drift wall locations. Thus, for example, the assumed limit for CO is the Saskatchewan limit of 25 ppm. Table 5 shows that we measured a truck CO concentration the first day of 6.0 ppm. This 6.0 ppm CO reading is (6.0/25) x 100 = 24.0% of the assumed limit, the value that is listed in Table 8.

Presenting the readings as percentages of the assumed limits allows us to compare them on an equal basis independent of the different numerical values for the limits. Examination of the truck averages in Table 8 shows that TPM at 265% of its assumed limit of 10 mg/m^3 is by far of greatest concern with NO_2 at 87% second and TRPM at 61% third. It is quite likely that, had the auxiliary drift ventilation been used, TPM would have been controlled somewhat better.

Table 8. Operating Concentration as % of Assumed Limit

Date Monitored	Location	CO, %	NO, %	NO_2, %	SO_4, %	SO_2, %	TPM, %	TRPM, %	RCD, %	OLD AQI, %	NEW AQI, %
					Truck						
11/26/84	BO489-BO4	24	11	151	1.3	1.4	310	-	50	84	64
11/27/84	BO489-BO4	20	4.4	56	1.4	1.5	220	-	28	42	30
11/28/84	BO489-BO4	28	8.7	58	1.3	1.4	-	46	35	50	37
11/29/84	BO489-BO4	-	7.2	50	-	-	-	64	25	-	-
11/30/84	BO489-BO4	22	23	82	3.3	3.5	-	72	54	79	55
Avg.		24	14	87	1.8	1.9	265	61	39	59	44
					Drift wall						
11/26/84	BO489	20	10	73	1.0	1.1	3530	-	148	159	102
11/27/84	BO489	19	6	42	1.2	1.2	151	42	23	36	25
11/28/84	BO489	24	11	-	0.9	1.0	-	282	9	23	8
11/29/84	BO489	20	18	40	2.1	2.3	-	104	29	46	32
11/30/84	BO489	22	23	67	3.1	3.3	-	186	128	144	94
Avg.		21	14	56	1.7	1.8	1840	154	67	80	54

One important observation is that the NO measured on the truck is only 14% of its assumed limit indicating that NO has probably been converted to NO_2. The apparent cause of high NO_2 readings, as suggested earlier, is long NO residence times, the problem being exaggerated by the observed recirculation through the drifts BO4, - 33165 - P.E.5, - #7 extension. It appears that elimination of this recirculation could result in large NO_2 reductions with little probability of NO increasing to levels anywhere near the assumed limit. The 151% of assumed limit for the first days truck NO_2 reading suggests that more diligence must be exercised in avoiding such recirculation when bolting since the bolter apparently emits higher quantities of NO_2.

The drift wall percentages show TPM to be 1840% and it is obvious that TPM is the critical pollutant. TRPM is second most critical at 154%, old AQI is 3rd at 80% and RCD is 4th at 67%. RCD is the greatest contributor to the AQI. NO_2 appears to be somewhat lower on the drift wall, but in general the comments made about NO_2 on the truck hold true there also.

Because the concentration of each pollutant is linearly related to the CO_2 concentration, once the characteristic curves have been developed, it is not necessary to continually monitor all pollutants. We can instead estimate the concentration of any pollutant by measuring the CO_2 concentration and using the characteristic curve along with this CO_2 concentration to find the corresponding pollutant concentration.

We can also determine the CO_2 concentration at which each pollutant reaches its assumed limit by extending the least squares line to the point where it intersects the assumed limit (horizontal line imposed on each plot). These "CO_2,% at assumed limit" values are presented in Table 9. The

CO_2 concentration in the drift should be limited to approximately .14% to control TRPM in the drift. To control the AQI in the drift, the drift CO_2 concentration should not exceed .18%. To control NO_2 on the truck the CO_2 concentration on the truck should not exceed .187% (assuming the recirculation conditions remains a distinct possibility). If the direct-firing of propane were discontinued, revised limits could be found by measuring the background concentrations as before and replotting the characteristic curve through the new background point, by the procedure discussed in Appendix I.

Table 9 lists all the pollutants in order from least to most critical (highest to lowest CO_2,% of assumed limit values). NO_2 is the critical pollutant on the truck with 'old AQI' second. 'Old AQI' is most critical in the drift with TRPM second.

The question which might now be asked is "what level of control is desirable?" We have defined "desired control" in terms of the slope of the characteristic curve and have decided that it would be desirable (but probably not practical), to control a pollutant by reducing the slope of its characteristic cuve until the particular pollutant reaches its TLV at the same time CO_2 reaches its TLV of 0.5%. We have therefore defined a term called "desired control efficiency with CO_2 limiting" which is the percentage by which the slope of the characteristic curve must be reduced to achieve this desired level of control. Mathematically the "desired control efficiency with CO_2 limiting" is expressed as follows:

$$\frac{\text{Pollutant slope} - \text{Pollutant slope that intersects the TLV at 0.5\% } CO_2}{\text{Pollutant slope}} \times 100$$

Table 9. Various Calculated Parameters

CO_2, % at Assumed Limit

	CO	NO	NO_2	SO_4	SO_2	TRPM	RCD	OLD AQI
				Truck				
CO_2, %:	.476	.667	.187	3.05	2.87	.250	.256	.211
				Drift Wall				
CO_2, %:	.494	.691	.275	3.05	2.87	.142	.195	.180

Pollutant Ranking, Least to Most Critical

Truck
SO_4, SO_2, NO, CO, RCD, TRPM, OLD AQI, NO_2
Drift Wall
SO_4, SO_2, NO, CO, NO_2, RCD, OLD AQI, TRPM

Desired Control Efficiency with CO_2 Limiting

CO, %	NO, %	NO_2, %	SO_4, %	SO_2, %	TRPM, %	RCD, %	OLD AQI, %
			Truck				
7	-43	82	-671	-624	66	64	76
			Drift Wall				
2	-50	59	-693	-646	94	80	84

The values are presented in the bottom part of Table 9 where we see that by this criterion, truck SO_4, SO_2 and NO are over-controlled, while the desired amounts of control for the other truck on-board pollutants range from 6% for CO to 76% for AQI. Drift SO_4, SO_2, and NO are also over-controlled, and desired amounts of control for other drift pollutants range from 2% for CO to 94% for TRPM. The desired control efficiency values, of course, increase in the same order as the pollutant ranking -- least to most critical and these values will also change if direct-firing of propane in the background air is discontinued.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion:

1. While diesel pollutant concentrations in long dead end headings such as those in the development operation monitored require control, they are by far of secondary concern to the salt dust. Thus while for the most part diesel pollutant concentrations were well below assumed limits, salt dust concentrations were several times the proposed 10 mg/m^3 Saskatchewan limit for total particulate which also equals the ACGIH TLV for nuisance particles. Respirable salt dust appears to be less of a problem, but still exceeded the ACGIH TLV in the drift when auxiliary ventilation was not used. Unfortunately the study was not of sufficient duration to determine the total and respirable salt dust concentrations with the normal condition when auxiliary ventilation was used.

It is recommended, therefore, that the normal auxiliary drift ventilation be used to control the salt dust and with such control, drift concentrations of diesel pollutants should also be adequately controlled.

2. By a recently-developed modification to our data-presentation methodology we were able to present the overall pollutant CO_2 concentration data as characteristic curves. Thus while our past methodology allowed us to illustrate the diesel-effect only in this manner, the recent modification allows us to illustrate the diesel effect as well as the overall effect by presenting curves which include the background effect. This is especially important in mines such as Lanigan when direct-firing of propane in the intake air makes a contribution to the measured pollutant and CO_2 concentrations.

It is therefore recommended that the characteristic curves developed here be employed at once for making decisions about controls. However, any changes in the direct-firing of propane in the intake will require that the curves presented be modified to pass through the new background data points determined by remeasuring the background pollutant and CO_2 concentrations.

3. The background pollutant concentrations resulting from direct-firing of propane make a small but significant contribution to the diesel pollutant concentrations measured at the face. The background CO_2 concentration which is a combination of natural CO_2 in outside air and CO_2 from direct-firing of propane in the intake air contributes over half of the CO_2 concentration measured at the face. Therefore, the characteristic curves must be adjusted on the basis of background measurements. This gives further support for the recommendation in 2. above.

4. The weekly average slopes of the pollutant characteristic curves are compared with slopes from 9 other studies in the tabulation below (these results include vehicles with and without catalytic converters):

Weekly Average Slopes for Characteristic Curves and Typical Values Found in Earlier Work

Pollutant	Weekly Average slope, ppm/%		Slopes found in other studies, ppm/%	
	Truck	Drift	Range	Median
CO	73	70	14-105	67
NO	34	37	46-93	72
NO_2	23	10	7-28	13
SO_4	.33	.33	0.4-4.0	2.0
SO_2	.71	.71	4-10	7
TRPM	22	154	16-31	21
RCD	16	30	6-17	10.5
OLD AQI	43	67	23-46	39.5

For the truck and drift these values compare to the other studies as follows:

	Truck	Drift
Below range:	NO, SO_4, SO_2	NO, SO_4, SO_2
In range, but below median:		NO_2
In range, but above median:	CO, NO_2, TRPM, RCD, AQI	CO
Above range:		TRPM, RCD, AQI

5. Of the diesel pollutants, NO_2 appears to be the one of greatest concern in the present study. NO and NO_2 readings by the Palmes samplers were all reduced by the correction factors developed from readings taken alongside the Ecolyzer in the drift. This assumes the Ecolyzer to be correct, but there is also a possibility that the Ecolyzer was reading low due to negative interference even with its interference filter and that the readings are much higher than reported here. While this may not be a concern for NO, which is well below the assumed limit, it would put NO_2 way above its assumed limits.

Therefore it is recommended that steps be taken to reduce NO_2. Such a reduction could be achieved by reducing the residence time of NO in the mine air since NO_2 is produced primarily by reaction of NO with oxygen in the air and the reaction is time dependent. Thus ventilation air recirculation such as reported here must be avoided since it can result in high NO_2 concentrations from relatively low NO concentrations. Furthermore, series ventilation of the diesel operations should be avoided where distances and, consequently, residence times are long. The John Deere bolter also needs special consideration since much higher NO_2 concentrations were reported near the bolter. The exhaust air from the bolting operation should, therefore, not be used to ventilate other mine areas.

6. The truck and drift pollutant concentrations expressed as percentages of assumed limits averaged for the week were in order from least to greatest:

Average Operating Concentration as % of Assumed Limits for Week

Truck

SO_4	SO_2	NO	CO	RCD	NEW AQI	OLD AQI	TRPM	NO_2	TPM
1.8	1.9	14	24	39	44	59	61	87	% 265

Drift wall

SO_4	SO_2	NO	CO	NEW AQI	NO_2	RCD	OLD AQI	TRPM	TPM
1.7	1.8	14	21	54	56	67	80	154	1840

The CO_2 percentages at the assumed limits vary for the truck on-board readings: from 3.05% CO_2 for SO_4 control to .187% CO_2 for NO_2 control, and for the drift: from 3.05% CO_2 for SO_4 control to .185% for old AQI control. Based on these findings it is recommended that for the operation studied, the Lanigan Mine should monitor CO_2 and take corrective action when the CO_2 concentration exceeds 0.18%. This CO_2 limit will, or course, change with changing background as discussed in Appendix I.

7. Air flow measurements alone are not an adequate means of assuring satisfactory air quality in operations such as the one studied. While air flow measurements are needed to identify and eliminate recirculation, the only way to be assured of satisfactory air quality is to measure the concentrations of the various pollutants of concern.

It is recommended that, in addition to frequent CO_2 concentration checks, the various pollutants also be spot checked on occasion. NO_2 checks can be especially useful in locating recirculation or other causes of long residence time for the mine air diesel emissions.

8. The fuel sulfur content upon which these conclusions are based was virtually zero. Any change in fuel supply which results in increasing fuel sulfur levels will tend to invalidate these conclusions. Therefore, if such a change is made, it will be worthwhile to reevaluate the findings of the study and formulate new conclusions and recommendations. For example, a high fuel sulfur content may result in a recommendation for removal of the PTX catalytic converter.

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2) TLVS - Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1983-84. American Conference of Governmental Industrial Hygienists, 6500 Glenview Ave., Bldg. D-5, Cincinnati, OH 45211 (1983).

3) Johnson, J.H. and Carlson, D.H., "A Study of Diesel Pollutants in an Underground Production Metal Mine Using an Advanced Monitoring and Data Analysis Methodology," Final Report to CANMET, Contract No. OSQ82-00210, March 1984.

4) Johnson, J.H., Carlson, D.H. and Schimmelman, M.K., "Monitoring and Control of Mine Air Diesel Pollutants: Mine Measurements and Interpretation Relative to Standards and Control Rechnology, Design and Development of a Tailpipe Emissions Measurement Apparatus (EMA-2) and On-Board Drift Ventilation Systems Evaluation," Annual Task Report to the U.S. Department of Interior, Bureau of Mines for Contract No. J0199125, February 15, 1984.

5) Osborne, M.D., Johnson J.H., and Reinbold, E.O., "The Effects of Catalysts and a Particulate Trap on Diesel Emissions in Underground Mining, CIM Bulletin, to be published.

6) "Health Implications of Exposure of Underground Mine Workers to Diesel Exhaust Emissions - An Update," Report to CANMET by Ian W. French and Associates Limited for Contract No. 23SQ.23440-2-9062, April 20, 1984.

APPENDIX I

Figure I-1 illustrates how the characteristic curves for the various pollutants were developed. Hypothetical truck CO measurements are shown to illustrate the procedures used. The same steps were involved for each pollutant:

1. Each day's CO concentration reading on-board the truck was corrected by subtracting the simultaneously-measured mine intake concentration reading to give the 'truck - BG' CO value.

2. The average $(CO-BG)/(CO_2-BG)$ ratio for the week is determined; this average ratio is the slope of the CO characteristic curve and is represented by the line through the origin in Figure I-1. This slope is characteristic of the diesel emissions only (background removed).

3. Background CO and CO_2 concentrations for the week are averaged and the characteristic curve is constructed by passing a line of slope determined as in 2 above through the point representing this average.

4. The actual uncorrected truck on-board CO and CO_2 concentration readings are plotted on the same coordinates to show how well these line up with the characteristic curve.

The slope is determined with the background data removed because we know that when the diesel-produced CO_2 concentration is zero, the diesel-produced CO concentration must also be zero. Thus with the background removed we know that one point on the curve used to determine the slope must be the origin and this point is not subject to measurement error.

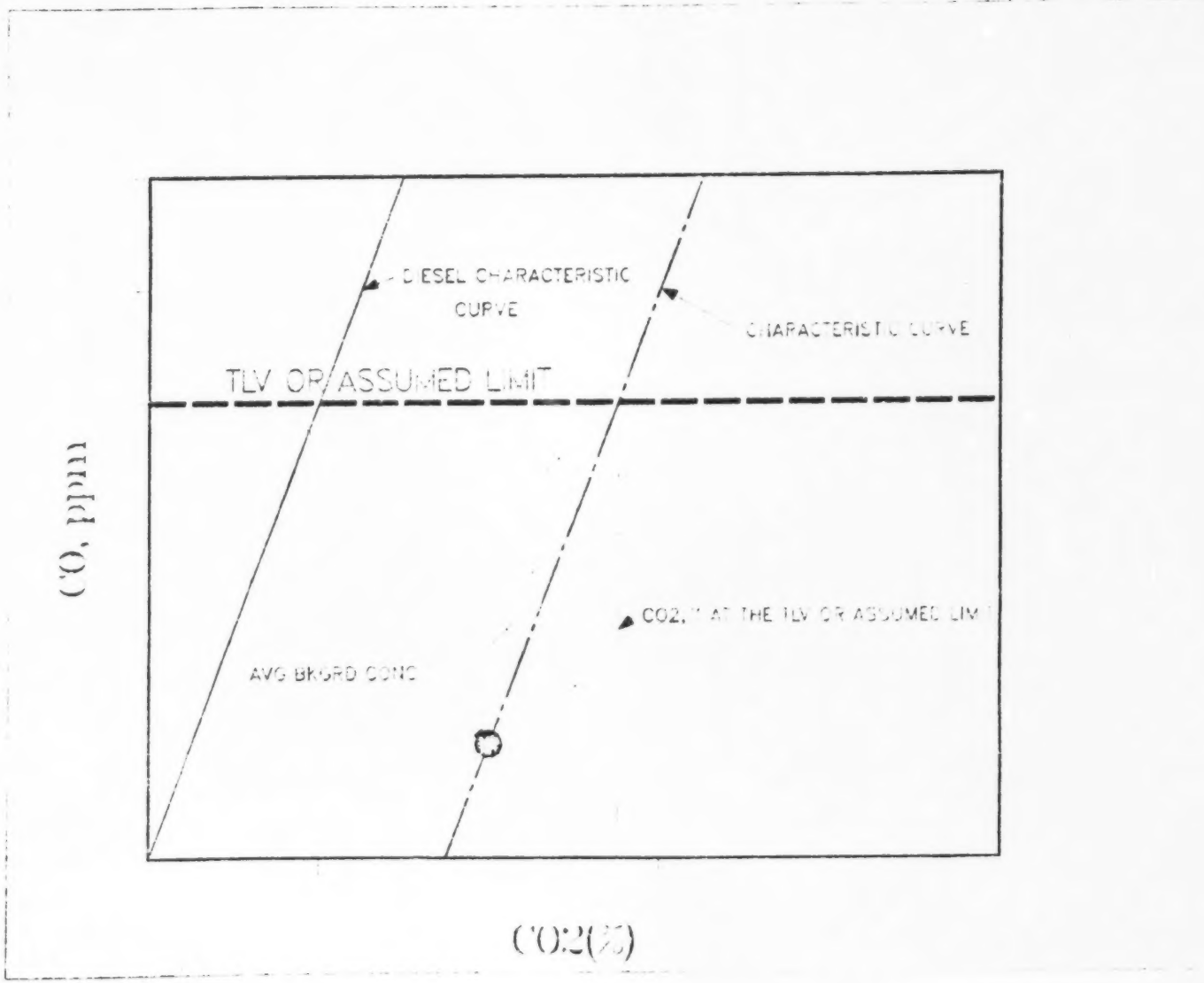

Figure I-1. Illustration of procedure used to develop the characteristic curves presented in this report.

Figure I-1 also has general utility for varying background readings. Thus for example, if less propane were to be burned in the intake we would simply construct a new curve of the same slope through the new background pollutant and CO_2 concentrations representing this condition. The curve would, or course, be parallel to the original so could be constructed without involving mathematical computation.

APPENDIX II

NO & NO_2 Measurement Procedures and Corrections

Table II-1 compares NO and NO_2 readings in the drift by the Ecolyzer 7230 instrument with those by the Palmes samplers. The first day's readings are unusual and the difference is thought to be due to the bolter so these ratios were rejected along with two other ratios as shown in Table II-2.

The values rejected were simply judged to be too far from the others. The remaining ratios were averaged to arrive at the correction factors used to calculate NO and NO_2 values presented in the report.

The overall calculation procedure for NO and NO_2 is presented in Figure II-1.

Table II-1. Daily drift NO and NO_2 concentrations by the Ecolyzer 7230 and Palmes samplers and ratios as measured.

Date	Instrument		Palmes		Ratio Palmes/Instr.	
	NO_2	NO	NO_2	NO	NO_2	NO
11/26/84	.718	2.76	4.517	3.435	6.3	1.2
11/27/84	.484	2.44	1.714	8.115	3.5	3.3
11/28/84	.660	1.40	1.303	9.618	1.8	6.9
11/29/84	.714	4.15	1.387	11.695	1.9	2.8
11/30/84	1.15	6.70	2.734	14.298	2.4	2.1

Table II-2. Daily drift NO and NO_2 concentrations by the Ecolyzer 7230 and Palmes samplers and ratios as used.

Date	Instrument		Palmes		Ratio Palmes/Instr.	
	NO_2	NO	NO_2	NO	NO_2	NO
11/26/84	.718	2.76	4.517	3.435	X	X
11/27/84	.484	2.44	1.714	8.115	X	3.3
11/28/84	.660	1.40	1.303	96.18	1.8	X
11/29/84	.714	4.15	1.387	11.695	1.9	2.8
11/30/84	1.15	6.70	2.734	14.298	2.4	2.1

X = Rejected values.

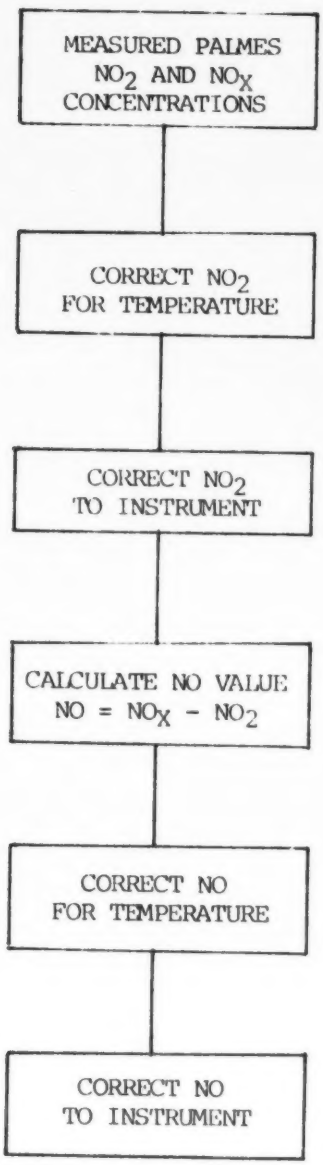

Figure II-1. Calculation procedure for correcting NO and NO_2 measurements by Palmes samplers.